BOD_5 REMOVAL IN SUBSURFACE FLOW CONSTRUCTED WETLANDS

WITH RESPECT TO ASPECT RATIO AND INFLUENT LOADING

A Thesis

by

REBECCA HOBBS MELTON

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2005

Major Subject: Biological & Agricultural Engineering

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Approved as to style and content by:

Richard Weaver (Co-Chair of Committee)	Ann Kenimer (Co-Chair of Committee)
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ABSTRACT

BOD_5 Removal in Subsurface Flow Constructed Wetlands

with Respect to Aspect Ratio and Influent Loading. (May 2005)

Rebecca Hobbs Melton, B.S., Utah State University

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Dr. Ann Kenimer

The frequency of on-site systems for treatment of domestic wastewater is increasing with new residential development in both rural and low-density suburban areas. Subsurface flow constructed wetlands (SFCW) have emerged as a viable option to achieve advanced or secondary treatment of domestic wastewater. The pollutant removal efficiency in SFCW depends on design parameters. Many of these factors have been investigated while others such as aspect ratio, design of water inlet structure and method of dosing the wetland have yet to be fully examined. This study examined the effect of aspect ratio and header design on BOD_5 removal efficiency as well as the impact of flow rate on flow distribution in a SFCW. An aspect ratio of 4:1 achieved 10% greater removal of organic matter than a 1:1 ratio. Tracer studies demonstrated that wetlands loaded at a constant rate of 3.8 L/min and 7.6 L/min experienced preferential flow. In addition, tracer studies showed wetlands with leaching chambers as headers failed to achieve equal flow distribution. An improvement in effluent water quality was achieved by replacing the leaching chamber for a perforated manifold as the inlet structure. This study demonstrated the importance of the careful selection of aspect ratio and means by which water is introduced to the wetland in the design of SFCW.

ACKNOWLEDGEMENTS

First and foremost I'd like to thank my husband Brad for all of his support throughout the process which included, but was not limited to, digging holes in gravel, going with me on sampling trips, reading my drafts, listening to me complain, and loving me through it all. Secondly, I appreciate Dr. Richard Weaver for affording me the opportunity to come to Texas A&M and learn more about the process of research and analysis. I am grateful for the guidance provided by Dr. Ann Kenimer, who happens to be one of the best university professors I've had the privilege of taking a class from. Dr. Russell Persyn also offered invaluable advising that helped me keep my sanity. I'd also like to thank Dr. Bruce Lesikar for inspiring me in the field of onsite wastewater treatment. I am thankful for the funding from the USEPA 319h non-point source pollution program through the TCEQ which supported this research. My co-workers Dr. Alexandria Graves and Martha Cepeda-Hernandez offered me much needed support and encouragement through the year and a half I worked with them. I owe gratitude to my good friend Brittany Pfister because without her I may have never finished writing this thesis. Lastly, none of this work would have been possible without the help of Heidi Mjelde (who deserves an honorary Masters of her own), Faith Torres, and Jenn Waters in the field and lab.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION

The Texas Commission on Environmental Quality (TCEQ) reports that a third of the new houses built in Texas use onsite wastewater treatment. With rapid population growth in both rural and low-density suburban areas of Texas, local agencies permit as many as 50,000 new onsite systems annually (TAMU, 2005). In many areas of Texas, site conditions are not conducive for use of conventional treatment of effluent water from a septic tank, due to poor soils or drainfield requirements that are too large for the size of the property. Without secondary or advanced treatment, the soil will not adequately absorb the organic and microbial pollutants. Without proper absorption, these pollutants may potentially be carried in runoff and impair the surface waters of the watershed.

Subsurface flow constructed wetlands (SFCW) have emerged as a viable option to achieve advanced or secondary treatment of domestic wastewater. The United States Environmental Protection Agency (USEPA) defines an appropriate technology as a system that is affordable, operable and reliable (USEPA, 2000b). In small communities and rural areas it is essential that an onsite system meet these criteria so the treatment technology does not fail and lead to subsequent nonpoint source water quality issues. If properly used, constructed wetlands can meet USEPA's appropriate technology standards given their low operation and maintenance costs. The SFCW can provide

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needed reduction in organic matter to increase the life of a drainfield and prevent clogging of the soil (Bounds et al., 1998, Cooper and Hobson, 1989, and USEPA, 2000a). SFCWs can also provide sufficient treatment for wastewater through land application of the treated water after disinfection (Nerella et al., 2000).

The pollutant removal efficiency of a SFCW depends on multiple factors such as influent wastewater quality, hydraulic and pollutant loading, climate, and the physical characteristics of the system (USEPA, 2000b). Some examples of physical characteristics include water and media depth, aspect ratio, media selection, and vegetation. As with many other natural wastewater treatment systems, pollutant removal processes in SFCW are not well understood because they have complex and less controllable flow patterns and have variable reaction rates (USEPA, 2000b). Because these natural treatment processes are not well defined, design criteria to this point should be used as a general outline in design rather than as a recipe for guaranteed results (TVA, 1991).

As part of a 319-H project funded by the USEPA through TCEQ, the Soil Microbiology Lab in the Soil and Crop Sciences Department at Texas A&M University investigated SFCW function and design. Over the course of the last 5 years, data has been collected by the Soil Microbiology lab from 33 wetlands scattered around Texas including a test SFCW in College Station, TX. The data has been used to better assess the efficiency of SFCW as well as the effect of varying design parameters. All systems were sized based on design criteria for five day biological oxygen demand (BOD_5) removal as recommended by the USEPA (1993a). The steps in sizing are as follows:

1) Determine influent BOD_5 concentration, average hydraulic load, and desired BOD_5 concentration for the effluent;
2) Select a water level depth and fill medium size and type;
3) Calculate the porosity of the medium;
4) Select a length to width ratio;
5) Determine the surface area required using the following equation:

$$A_s = Q[\ln(C_o/C_e)]/(K_t dn) \quad (1)$$

where:

A_s=surface area (m^2),
Q=hydraulic load (m^3/d),
C_o=Influent BOD_5 (mg/L),
C_e=Effluent BOD_5 (mg/L),
K_t=temperature dependent rate factor (d^{-1}),
d=average wastewater depth (m),
n=porosity;

6) Use Darcy's equation to determine if the hydraulic conductivity of the medium is adequate (USEPA, 1993b).

Variation in design between different sites can be limited to the way the water was loaded into the wetland, aspect ratio, septic effluent composition, as well as deviation in actual hydraulic and organic loading from the estimated values used in the design. Many systems in the project have consistently achieved secondary quality effluent (30/30 or 20/20) while others achieve only advanced treatment (improvement in BOD_5 and TSS). The variable results in effluent quality, even though all wetlands were sized similarly, indicate that parameters beyond those considered in the EPA design guidance may have an impact on the overall effectiveness of the system. If the effects of these additional parameters can be better understood, the design criteria for those parameters can be further developed and optimized. By following the optimized guidelines, the SFCW technology can be better utilized for consistent secondary treatment.

The purpose of this research was to investigate three design parameters, aspect ratio, hydraulic loading, and header design, more closely so that their impact on SFCW performance may be optimized in future wetland design. In addition, the header design research focused on a comparison of the traditionally used perforated pipe with a leaching chamber, which has recently come into use in SFCW.

Objectives

1) Determine the effect of a 1:1 verses 4:1 aspect ratio of a SFCW on BOD_5 removal efficiency.

2) Evaluate the effect on SFCW flow pattern of varying flow rate and method of loading.

3) Evaluate the effectiveness of a leaching chamber as a header for SFCW.

CHAPTER II

ASPECT RATIO FOR SUBSURFACE FLOW CONSTRUCTED WETLANDS

Introduction

In designing a subsurface flow constructed wetland (SFCW) for the on-site treatment of domestic wastewater, many parameters are individually selected for a particular design. Length and width configurations are among these parameters. In this thesis, the length to width ratio is referred to as the aspect ratio. According to Steiner and Freeman (1989), the length to width ratio is the key for configuring the system to minimize short-circuiting and maximizing contact with the cross-sectional area of the SFCW.

The USEPA (1993b) evaluated 19 systems with aspect ratios ranging from 1.4:1 to 17:1, but no relationships were found between BOD_5 or TSS removal and aspect ratio. A limitation of that study was the wide range in sizing, hydraulics, and other operational parameters. Most of the systems were significantly larger than those that would be used for residential on-site treatment. In addition, the wetlands were usually used as polishing after other secondary treatment and received low BOD_5 inputs ranging from 5 mg/L to 51 mg/L. The usual range of effluent BOD_5 concentrations from most residential septic tanks is 100 to 200 mg/L (TCEQ, 2005). Chen et al. (1993) points out however, that theoretical analysis based on equations used to describe flow and kinetics of SFCW indicates, if other parameters are fixed, there is a strong relationship between aspect ratio and BOD_5 removal, and therefore to have a valid comparison between multiple systems other parameters must be similar.

Prior examinations of aspect ratios for small wetland systems are limited to an experiment conducted by Bounds et al. (1998). They used three wetlands with aspect ratios of 4:1, 10:1 and 30:1 with surface areas of 25 m^3 and water depths of 0.30 m treating the same septic tank effluent. Their conclusion was that aspect ratio did not make a difference in BOD_5 removal. The 30:1 aspect ratio wetland had a significantly less negative oxidation-reduction potential suggesting it was less anaerobic than the other two aspect ratios. Although statistically significant differences in BOD_5 reduction were not provided by the three aspect ratios, there was a consistent trend of increased treatment with increased aspect ratio.

Although Bounds et al. (1998) conducted studies using wetland cells with areas similar to those commonly used for residential on-site treatment, it is difficult to apply their conclusions to system design. First, they used a detention time of 4 d which is much longer than detention times usually observed in typical residential systems (Nerella et al., 2002). In addition, in most residential systems, site conditions are rarely conducive to a system having wetland cells as long as those used in the 10:1 and 30:1 systems. Further, the large aspect ratios used in the study conflict with suggestions in the literature of using a smaller aspect ratio to minimize potential clogging and maintain surface flow (Steiner and Freeman, 1989 and Watson and Hobson, 1989).

Steiner and Freeman (1989) suggest that an aspect ratio of 1 or less allows solids that settle out in the front wetland to be distributed over a larger portion of the wetland. USEPA (2000a) suggested the aspect ratio should be between 2:1 and 1:2. Watson and Hobson (1989) suggest that the aspect ratio may need to be lower than 3:1 and potentially even lower than 1:1 to ensure flow remains subsurface. They do, however, state that if an aspect ratio of less than 3:1 is used, the inlet and outlet structures become very important in overcoming potential short-circuiting due to the increased width. Steiner and Freeman (1989) state that if even distribution is achieved and the hydraulic capacity is not exceeded, a large aspect ratio is not needed because plug-flow should occur.

The objective of our investigation was to compare BOD_5 reduction in wetlands with aspect ratios of 1:1 and 4:1 under similar BOD_5 and hydraulic loads.

Methods and Materials

The study was conducted using a plastic lined constructed wetland in College Station, TX. The wetland treated septic tank effluent from a four-bedroom duplex. From the duplex, the wastewater passed through two 1.89 m^3 septic tanks as pretreatment and then into a pump tank. The effluent of the wetland had been closely monitored for the five years it had been in operation and had consistently achieved better than secondary quality effluent (20 BOD_5/20 TSS).

The wetland was filled with 1-5 cm diameter gravel with a porosity of 32% (Stecher and Weaver, 2003). The water depth was 0.2 m. The 4.46 m by 9.34 m wetland was divided into four equal sections, having lengths of 4.67 m and widths of 2.23 m (fig. 2-1). Each cell was set up so that it could be loaded independently of the others. The inlet device was a 2 cm inside diameter PVC pipe with 3 mm holes drilled every 4 cm across its length. The pipe extended across the full width of the wetland. Water was loaded from a pump tank into the two front cells (1 and 2) and drained into the cell directly below (1 to 3 and 2 to 4) through a 10 cm inside diameter PVC pipe with 3 mm slots every 3 cm (Weaver et al., 2003).

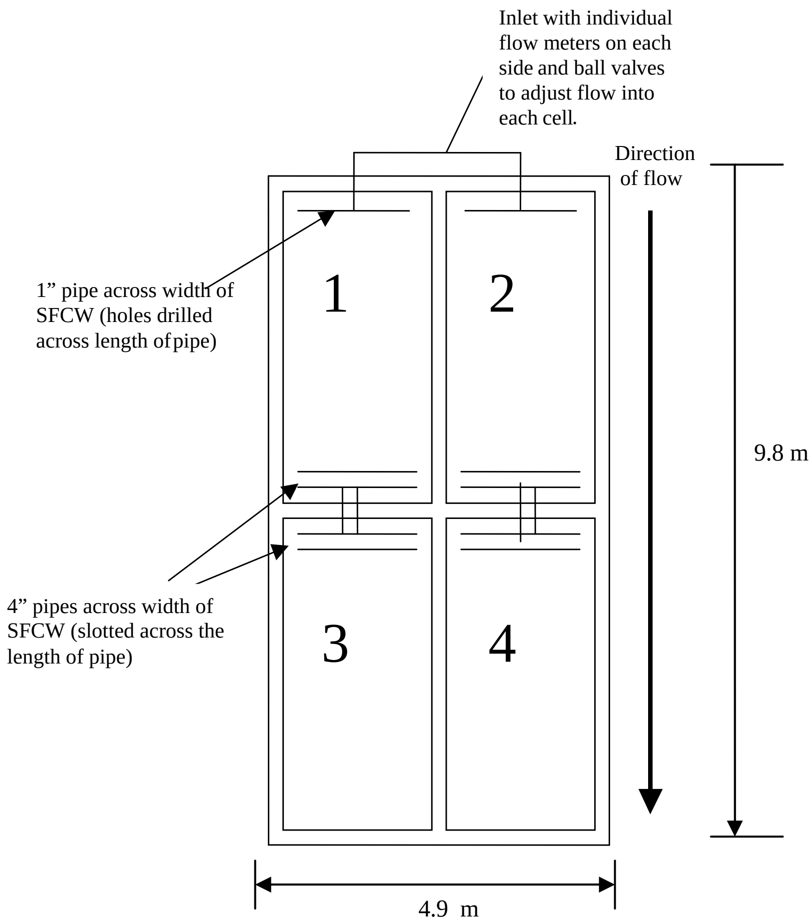


Figure 2-1. Experimental wetland configuration used in the aspect ratio study

To evaluate the impact of aspect ratio on BOD_5, the amount of flow going into each wetland cell was adjusted. To measure treatment efficiency of a 4:1 ratio, the majority of water from the pump tank was sent through one side of the wetland. Samples were collected from a sampling port at the end of cell 3 if the water was sent down cell 1 or from cell 4 if it went through cell 2. The samples were collected with a hand pump into 500 mL Nalgene bottles and taken back to the Texas A&M University soil microbiology laboratory for BOD_5 concentration analysis. The 4:1 ratio test was conducted on each side of the wetland for replication.

To measure BOD_5 removal for a 1:1 aspect ratio, the water was diverted with half going into cell 1 and half into cell 2. Samples were taken with a hand pump from the end of cells 1 and 2. These samples were taken back to the lab for BOD_5 analysis. Throughout the field study, flow into and out of each cell was monitored and recorded when samples were taken. During rainy periods the wetland was loosely covered with construction sheet plastic to prevent loading from precipitation. Comparisons of inlet and outlet flows indicated that water was not added to or lost from the system due to weather, leaks or evaporation.

One trial was conducted using the effluent from a single duplex (4 bedrooms) (low load). To increase the organic load, a second duplex was included (medium load). To further increase the $BOD_{5,}$ 0.9 kg of dog food (21% protein, 9% fat, 4 % fiber, 12% moisture) was added to the septic tank of one duplex daily (high load).

After the sample collecting process was completed, data collected from each of the three experiments were analyzed to compare percent removal of BOD_5. Statistical significance of differences in percent removal was determined using a Student-t analysis. All comparisons between BOD_5 reductions for the two aspect ratios were conducted using comparable areal influent loadings. Average influent BOD_5 concentrations were used to calculate percent removal rather than using the influent concentration on a given day. Averaged influent BOD_5 concentration values ranged from 69.2 mg/L to 150.1 mg/L. Daily hydraulic loading ranged from 0.22 m^3/d to 2.16 m^3/d.

Results

A summary of hydraulic and BOD_5 loading for the study as well as results for treatment efficiency for the two aspect ratios is shown in table 2-1.

Table 2-1. BOD_5 removal efficiency between 1:1 and 4:1 aspect ratios at low, medium and high BOD_5 loading.

	Aspect Ratio	**Number of Samples (n)**	**Flow (m^3/d)**	**Influent BOD_5 (mg/L)**	**Influent Load ($gm^{-2}d^{-1}$)**	**Effluent BOD_5 (mg/L)**	**% Removal**
Low Loading(*)	1:1	30	0.78±0.38(‡)	69.2±25.3	2.6±1.3	17.3±8.2	75.5±2.2 **a**(‡‡)
	4:1	20	0.78±0.25	76.6±24.6	2.9±0.9	5.44±3.5	93.2±0.9 **b**
Medium Loading(†)	1:1	8	1.33±0.31	90.6±14.3	5.8±1.4	20.4±3.6	77.5±1.4 **a**
	4:1	13	1.18±0.30	104.8±14.4	5.9±1.5	13.2±4.5	87.3±1.2 **c**
High Loading(††)	1:1	12	1.37±0.36	130.1±24.2	8.5±2.3	32.7±11.0	74.6±2.6 **a**
	4:1	10	1.23±0.30	150.1±23.9	8.8±2.2	18.4±8.8	87.3±6.6 **c**

(*) Aspect ratio test with the wetland treating water directly from one duplex. Values calculated from data in table A-1.
(†) Aspect ratio test with water from two duplexes being treated. Values calculated from data in table A-2.
(††) Aspect ratio test with water from two duplexes and dog food added being treated by the wetland. Values calculated from data in table A-3.
(‡) Averages shown with ± standard deviation.
(‡‡) Like letters indicate statistically similar ($p < .01$) values.

The percent removal of BOD_5 was significantly higher for the 4:1 aspect ratio than for the 1:1 ratio at all loading rates. For the aspect ratio of 1:1, increasing organic loading did not significantly reduce percent removal. For the aspect ratio of 4:1, increasing organic matter above low loading significantly reduced BOD_5 removal efficiency. Increasing the organic loading from a medium to high loading had no affect on the efficiency in the 4:1 ratio.

Data collected during the study provided an opportunity to examine the influence of hydraulic load with constant BOD_5 concentrations. A decrease in percent removal was observed as hydraulic load was increased while maintaining a particular BOD_5 concentration (table 2-2). Although the effect is not seen at low organic loadings, as the organic load increases toward the maximum capability of the wetland cell, the hydraulic loading begins to have a larger impact on the ability of the wetland to remove organic material.

Table 2-2. Comparison of removal efficiency with respect to similar concentrations but increased hydraulic flow halfway through the wetland and with the full length of the wetland.

Experiment Number	Number of Samples (n)	Daily Flow (m^3/d)	Influent BOD_5 (mg/L)	% Removal Half Length of the Wetland	% Removal Full Wetland Length
1[a]	30	0.34±0.21[d]	69.2±25.3	74.8±12.8[e]	90.6±4.0[h]
1	23	0.78±0.25	76.6±24.6	77.5±9.4[i]	92.6±5.0[e]
2[b]	8	0.67±0.16	90.6±14.3	76.9±5.9[f]	90.3±2.7[h]
2	13	1.18±0.30	104.8±14.4	58.2±12.0[i]	87.4±4.3[f]
3[c]	12	0.68±0.18	130.1±24.2	74.8±6.6[g]	91.6±4.0[h]
3	10	1.23±0.30	150.1±23.9	61.5±10.6[i]	87.3±6.6[g]

(a) Aspect ratio test with the wetland treating water directly from one duplex

(b) Aspect ratio test with water from two duplexes being treated

(c) Aspect ratio test with water from two duplexes and dog food added being treated by the wetland

(d) Averages shown with ± standard deviation

(e) Value calculated from data in table A-1

(f) Value calculated from data in table A-2

(g) Value calculated from data in table A-3

(h) Value calculated from data in table A-4

(i) Value calculated from data in table A-4

Wetland treatment efficiency is depicted with a linear relationship between BOD_5 load removal and BOD_5 loading (USEPA 1993b). This relationship is depicted in figure 2-2 for both the 1:1 and 4:1 aspect ratios. The slope of each of the least squared fit lines represents percent removal of BOD_5. The slopes, as well as the data presented in table 2-1, demonstrated that a 4:1 configuration is capable of removing around 10% more of the influent organic matter than a 1:1 configuration having the same surface area.

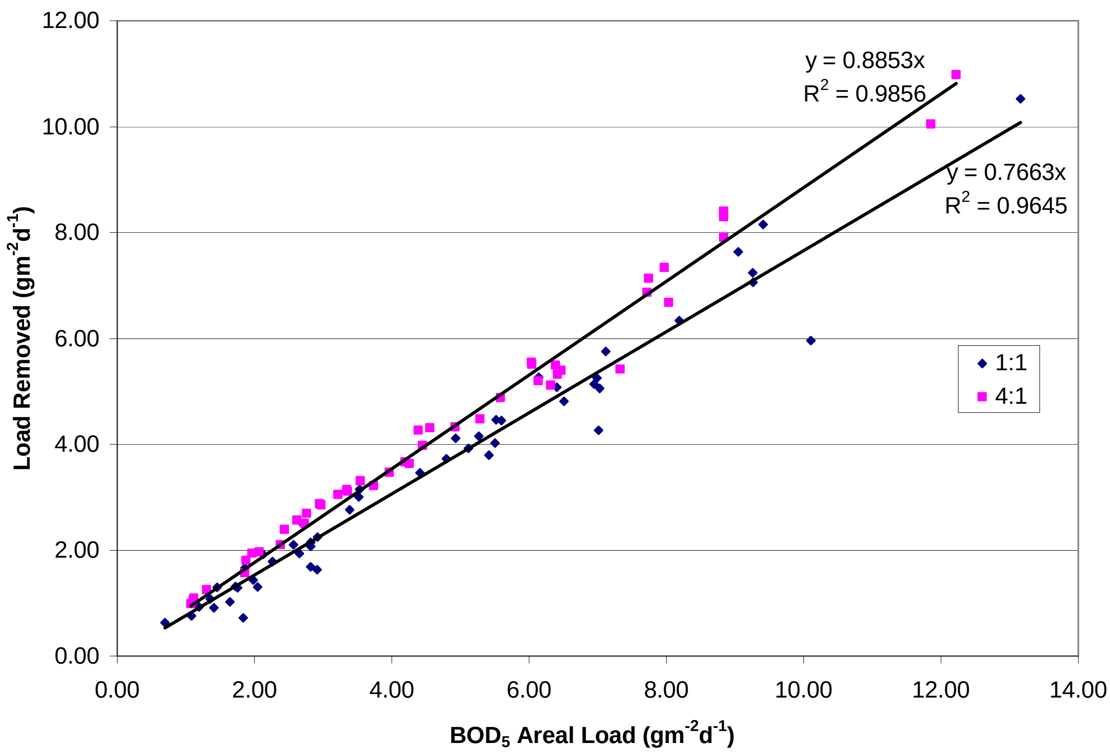


Figure 2-2. Load removed from the wetland with respect to the BOD_5 areal load.

Other statistical analysis showed that there was no difference between effluent BOD_5 values collected from cell 1 (20.2 ± 2.2 mg/L) and cell 2 (22.9 ± 2.1 mg/L) while each cell was receiving half of the flow. This supports the assumption that each side of the wetland acts as a replicate of the other and that the two parallel cells are acting similar to a 1:1 aspect ratio.

Discussion

In contrast to the conclusion of Bounds et al. (1998) that aspect ratio is not important; it was found to be important in this study. The reason for the different conclusion may be difference in aspect ratios examined. Bounds et al. (1998) used a minimum aspect of 4:1 while that was the maximum aspect ratio for this study. The conclusions from the data collected from this field study combined with Bounds et al. (1998) findings may indicate that although having an aspect ratio greater than one provides increased treatment, increasing the ratio past a certain point may not offer a significant improvement in BOD_5 treatment.

At some point, if the aspect ratio becomes too large, it may start having an adverse affect on the wetland. Using too small of a width results in an increased potential of clogging in the front of the wetland, and surfacing could be observed if the hydraulic conductivity, as described by Darcy's equation (2), becomes insufficient for the flow (USEPA, 1993b). This cross sectional area with respect to horizontal flow, A_c, is determined by:

$$A_c = Q/(k_s S) \qquad (2)$$

where

Q = average flow rate (m^3/d)
k_s = hydraulic conductivity of the medium (m/d)
S = hydraulic gradient (m/m).

As long as the selected design width and depth meet the requirements of Darcy's equation, surfacing should not occur in the short term. The potential for clogging in the front of the wetland can be reduced by the use and maintenance of an effluent filter in the septic tank as well as regular pumping of septic tanks to remove accumulated solids.

At first glance, 10% more BOD_5 removal may not appear to be very significant, but the impact of this difference can be seen when looking at percent removal with respect to achieving secondary quality effluent. To attain secondary quality influent in a wetland achieving 80% removal, the influent BOD_5 concentration cannot exceed 100 mg/L, whereas 200 mg/L influent can be effectively treated if the wetland consistently performs with a 90% removal capacity. The data collected further supports this notion since 27%, 63%, and 91% of the time the effluent of the 1:1 aspect ratio exceeded 20 mg/L BOD_5 at low, medium and high organic loadings respectively, while the 4:1 wetland only exceeded 20 mg/L (40 % of the time) at the high organic loading.

The scope of this study does not lend itself to a full determination of why an aspect ratio greater than one achieved improved BOD_5 removal. The reason most often suggested in the literature is more even flow distribution in longer beds since wider systems are more prone to short-circuiting (Steiner and Freedman, 1989; Watson and Hobson, 1989; Chen et al, 1993; TVA, 1993; USEPA, 1993a; Cothren, 2002). In this study, however, short-circuiting did not occur since flow tracer studies for this wetland demonstrated even flow with depth and width (Weaver et al., 2003).

The other possible explanation of the improved BOD_5 removal with higher aspect ratio may have to do with the removal capacity of the microbes. Figure 2-2 shows that the higher the influent BOD_5, the more BOD_5 is removed. Although the two configurations of the wetland were loaded with comparable aeral loading rates, these were actually only comparable "apparent" areal loading rates. USEPA (1993b) mentions that the derivation of an aeral loading rate assumes that the load is distributed equally throughout the entire wetland cell. In actuality, the organic loading is much heavier in the front of the wetland than in any other area because BOD_5 concentrations drop as water passes through the system. Mitchell and McNevin (2000) pointed out that, for a particular inlet concentration, if the flow rate is increased subsequently increasing the organic load, the removal rate will increase towards the maximum removal rate capable of the microorganisms. Because the front of a 4:1 ratio is loaded much heavier on a per unit length basis as compared to the 1:1 ratio, it is assumed that more organic matter is degraded in the front of the wetland. As indicated by USEPA (2000a), most of the removal is carried out in the first few meters. Once the wastewater has undergone heavy organic removal in the front of the wetland, the remainder of the length of the wetland provides additional polishing. A longer wetland would provide a greater length for the polishing to occur.

Despite the water moving through the wetland twice as fast on a per unit length basis in the 4:1 ratio as in the 1:1, the 4:1 ratio was still able to out perform the 1:1 ratio. This phenomenon can be explained with data shown in table 2-2. Although the findings shown in table 2-2 indicate that increasing the hydraulic loading adversely impacted treatment, the differences in percent removal at high and low hydraulic loadings were not as large as what would be expected. Expected effluent removal in

SFCW is often described by the first-order equation (USEPA, 1993a; Chen et al., 1993 and Mitchell and McNevin, 2000):

$$C_e = C_o * e^{K_t t} \tag{3}$$

where

C_o=Influent BOD (mg/L),
C_e=Effluent BOD (mg/L),
K_t=First-order rate factor (d^{-1})
t= Time (d).

The linear relationship in figure 2-2 supports the assumption that the SFCW in this study was operating under first-order kinetics. Increasing hydraulic load, as was done in the evaluation (figure 2-2), results in decreased hydraulic retention time (HRT). According to the equation for first-order kinetics, changes in HRT will have an exponential impact on effluent concentration. The differences in BOD_5 removal shown in table 2-2 do not reflect an exponential impact. This indicates that the first-order rate factor K_t must be slightly higher in the system operating under higher hydraulic loading to counteract some of the affect of a shorter HRT. A higher rate factor indicates the microbes are working at a point closer to their maximum removal capabilities. In short, although the microbes at a given distance from the inlet were given a shorter time to treat the water in the 4:1 aspect ratio, they were removing organic matter at a faster rate. Although the 4:1 aspect ratio was loaded in a manner that took advantage of the microbe’s removal capability, the hydraulic loading analysis as well as figure 2-2 reflect that the SFCW used in this study was operating under maximum treatment capacity, meaning the organic loading never stressed the microbes’ ability to treat the wastewater.

Although previously presented in the literature that aspect ratio has no impact on BOD_5 removal (Bounds et al. 1998), a comparison of a 1:1 ratio and a 4:1 ratio with similar design parameters demonstrated that there was an advantage to having an aspect ratio greater than one. This advantage of a larger aspect ratio providing additional treatment capacity needs to be weighed against other influences in the selection of the length and width values, such as topography, threat of clogging, surfacing prevention, and site layout. Depending on the water treatment goals, an appropriate ratio can be selected. For example, if the home is using the SFCW to improve the quality of water going to a leach field, using a larger aspect ratio to obtain the additional BOD_5 removal may not be necessary if the site layout is not conducive to the aspect ratio. On the other hand, if the SFCW is being utilized as a secondary treatment of water that will be land applied, then increasing the aspect ratio may be desirable so that treatment is improved.

Additional research should be conducted to examine the influence of changing aspect ratios to values in the range between 1:1 and 4:1. This may increase understanding of how much an aspect ratio needs to be increased above 1:1 to achieve increased treatment efficiency. In addition, an investigation could be done on impact aspect ratio may have on removal of other wastewater pollutants since this study was limited to BOD_5 removal.

CHAPTER III

INFLUENCE OF FLOW RATE ON WATER DISTRIBUTION IN A SUBSURFACE FLOW CONSTRUCTED WETLAND

Introduction

Subsurface flow constructed wetlands (SFCW) are usually dosed in two different ways, either with a pump tank or by gravity flow. The way that the water is introduced into the wetland may have an impact on how the water is distributed in the wetland.

Flow of water through a SFCW is complicated by occurrence of preferential flow, short-circuiting, or surfacing, all of which can be impacted by a number of design parameters. Design of SFCW on-site treatment may be enhanced through better understanding of the flow through the system. Flow is often assumed to be plug flow. The USEPA (2000a) explained that plug flow alone is not an appropriate description of flow. The agency noted studies by Sanford et al. (1995), and Liehr (2000) that demonstrated dispersion occurs in the flow. Overall, the USEPA (2000a) suggests that a plug flow reactor with dispersion most closely represents the actual conditions in a SFCW. Other parameters will effect the amount of dispersion occurring in the system, therefore impacting the flow. For example, the smaller the aspect ratio, the more dispersion is expected (USEPA, 2000a and Cothren et al., 2002).

A widely accepted method of analyzing flow through a SFCW is tracer studies. The ideal tracer for such a study should be inexpensive, nontoxic, easily measured, and flow with the water without retardation. Many different compounds can be used as tracers. Examples include bromide, chloride, atrazine, rhodamine, and dyes such as

FD&C blue no. 1 (Perillo et al., 1998; Butters et al., 2000; Kelly and Wilson, 2000; Kung et al., 2000, Ottman et al., 2000; and Rasmussen et al., 2000). Perillo et al. (1998) reported that FD&C blue no.1 (also called Brilliant Blue FCF dye) moves slower than wetting fronts at slow flow velocities and that bromide is retarded less than the Brilliant Blue FCF dye. Weaver et al. (2003) investigated water flow patterns in a SFCW with multiple tracer studies using Brilliant Blue FCF dye and Br^-. The investigations found that because of adsorption of dye on gravel, Brilliant Blue FCF dye is not an optimal tracer for flow experiments in SFCWs. The study showed that bromide flows with the water without retardation. This, combined with the facts that bromide is relatively inexpensive, easily measured with a probe, and if used in low concentrations does not pose a large risk of toxicity, makes bromide a suitable tracer for flow studies in a SFCW.

The tracer studies conducted by Weaver et al. (2003) and Stecher and Weaver (2003) using Br^- and dye examined a variety of design parameters and their effect on flow. Factors examined included water depth, load volume, header placement, and plants. The study found that plug flow did not occur in wetlands with depths of 17, 25 or 40 cm. A wetland with a 25 cm depth achieved uniform flow and even mixing with depth, while a wetland with a depth of 40 cm did not. Varying the hydraulic load from 38 L to 76 L per dose appeared to have no impact on the flow path. The placement of the header, towards the top or near the bottom of the wetland, had no impact on water distribution. Lastly, plant roots promoted preferential flow around root zones. Studies done by Weaver et al. (2003) and Stecher and Weaver (2003) were carried out in a manner simulating dosing from a pump tank.

The objective of this study was to continue the studies conducted by Weaver et al. (2003) and Stecher and Weaver (2003) by examining how other parameters, aside from those investigated in their studies, affect flow patterns. This study sought to investigate the impact of varying the flow rate into the wetland as well as dosing at a continuous rate on flow patterns through the wetland.

Methods and Materials

The tracer studies were conducted using an unplanted, plastic lined wetland cell 4.67 m long and 2.23m wide at two hydraulic loadings. The inlet device was a 2 cm inside diameter PVC pipe with 3 mm holes drilled every 4 cm across its length. The pipe extended across the full width of the wetland. The effluent device was a 10 cm inside diameter PVC pipe with 3 mm slots every 3 cm (Weaver et al., 2003). Both the inlet and outlet devices were located at a depth midway below the water level. Quartz river rock of 1 to 5 cm diameter normally used in a concrete mix was used as the wetland media. The porosity of the media was 32% (Setcher and Weaver, 2003). The water depth was measured as 20 cm. One pore volume (0.7 m^3) was calculated as the product of length, width, water depth, and porosity. Under daily operation, septic tank effluent from a four-bedroom duplex was delivered to the wetland through a 2 cm inside diameter PVC pipe with 3 mm holes every 4 cm across the length (Weaver et al., 2003).

The sampling ports constructed for the study were 1 cm inside diameter chlorinated polyvinyl chloride (CPVC) pipe. The pipe was tapered at the end by heating and collapsing the pipe to form a point over the last 1.5 to 2 cm. Two 3 mm holes were drilled into the pipe near the top of the taper to facilitate entry of water. Location of sampling ports in the wetland is shown in figure 3-1. Samples were taken from three depths at each sampling area. Pipes were pushed into the gravel so that the sampling zone was 17 cm, 10 cm and just barely under the water surface (4 mm).

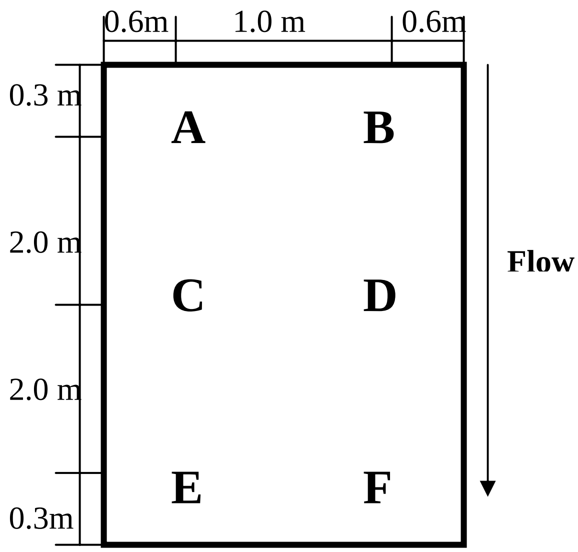


Figure 3-1. Sampling port layout for bromide tracer studies. Three depths were measured at each sampling station.

Bromide was selected as the tracer of choice for reasons described previously. The tracer consisted of 7 grams of NaBr mixed into a bucket filled with 19 L of tap water. The mixture was loaded into the wetland by submerging a pump, which was connected to pipe leading to the header, into the bucket. Because of the inlet configuration on the pump, only 15 L of the NaBr solution was actually loaded into the wetland. Samples were immediately collected from the first row of sampling ports as soon as the tracer was loaded. Immediately after injecting the tracer, the pump was moved from the tracer bucket into a bucket filled with plain tap water. This container was continually filled with tap water while the water was subsequently pumped into the wetland to achieve the desired continual loading. The two hydraulic loadings examined were continuous flow rates of 3.8 L/min and 7.6 L/min.

Samples were collected using an 8 mm outside diameter flexible plastic tube connected to a 60 ml syringe. Before a particular port was sampled, one full syringe volume was drawn from the port and then discarded. A second syringe volume was filled and then collected into a 120 mL plastic cup. This method of discarding the first water drawn and then keeping the second sample was used to prevent standing water trapped in the sampling port from being taken as the sample. Samples were collected every 6 minutes during pumping for both hydraulic loadings. All samples were brought back to the Texas A&M University Soil Microbiology lab to be analyzed using a Br^- selective electrode (Orion 9435, Beverly, MA).

Samples were analyzed with a Br^- selective electrode in the lab and output values of mV were recorded. To transform this data into concentration of NaBr, calibration curves were created. Known concentrations (1, 2, 5, 10, 20, 50, and 100 ppm) of NaBr in tap water from each site were measured with the probe. The mV values for each concentration were graphed with respect to the log of the concentration. A least squared fit was established for each graph and an equation for each line was developed. Concentrations for each sample were derived using the equation of best-fit line. The probe was recalibrated using the described methods approximately every 60 samples to avoid error due to drift.

Results

The breakthrough curves for the hydraulic loading of 3.8 L/min are depicted in figure 3-2. The resulting calibration curves are shown in appendix B.

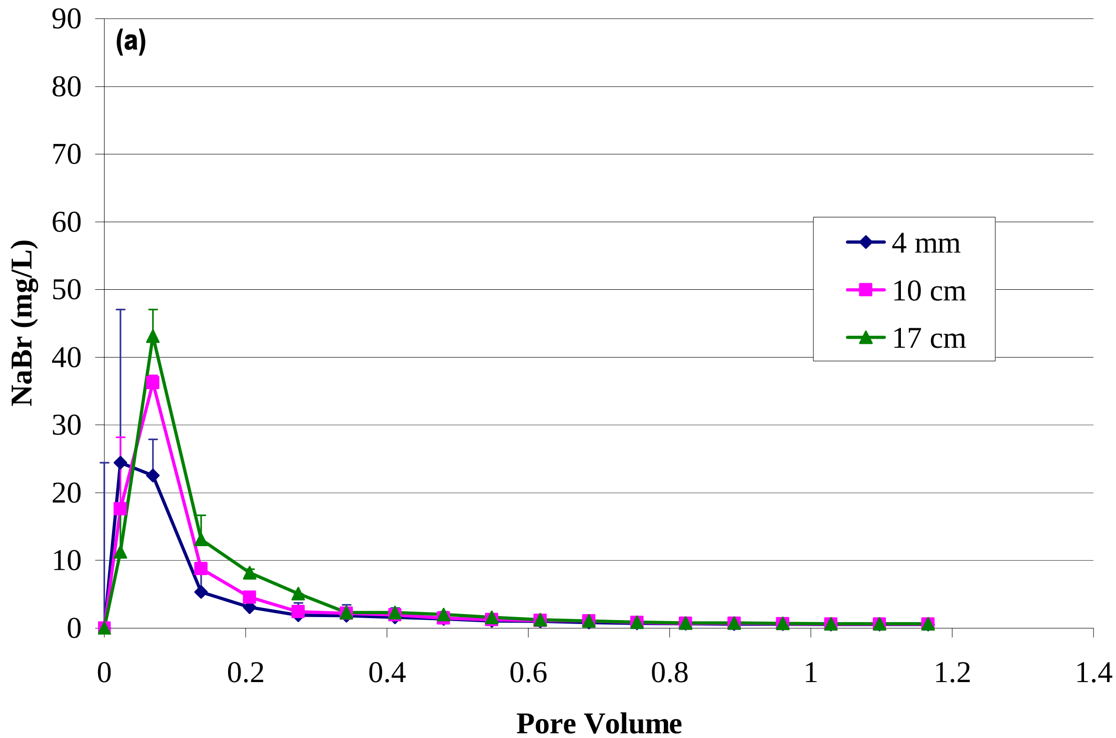
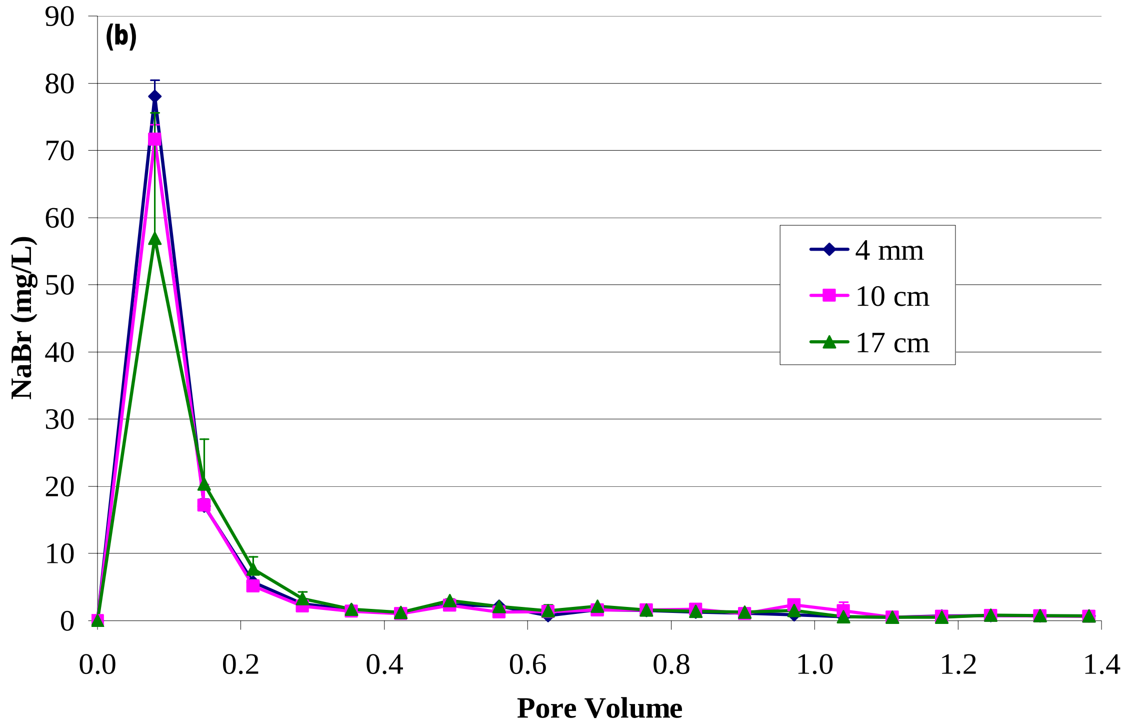


Figure 3-2. NaBr concentrations at various depths measured at (a) front, (b) middle, and (c) end for a continuous hydraulic loading of 3.8 L/min following addition of a bromide tracer to the inlet. Bars show one standard deviation.



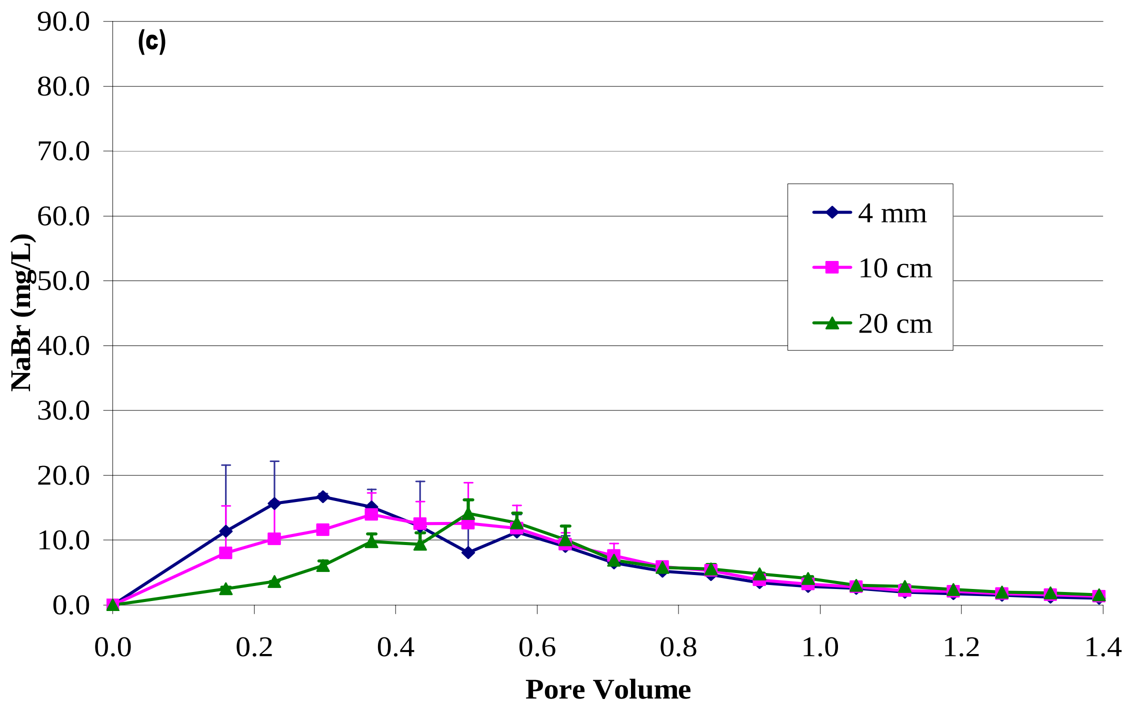


Figure 3-2. (continued).

Peak concentrations occurred in the front of the wetland at 0.06 pore volumes (figure 3-2a). The peak concentration occurred soon thereafter halfway down the length of the wetland cell after only 0.07 pore volumes (figure 3-2b). By the end of the wetland, (figure 3-2c) the peaks were occurring after pore volumes of, 0.3, 0.35, 0.5 at depths of 4 mm, 10 cm and 17 cm respectively (figure 3-2c). By 1.3 pores volumes it appeared that most of the tracer had left the wetland. There is a wide range of values for the peak concentrations for the different depths except for the 4 mm and 10 cm depth at the midpoint.

Similar observations can be made about the breakthrough curves of water flowing at a constant 7.6 L/m rate (fig. 3-3).

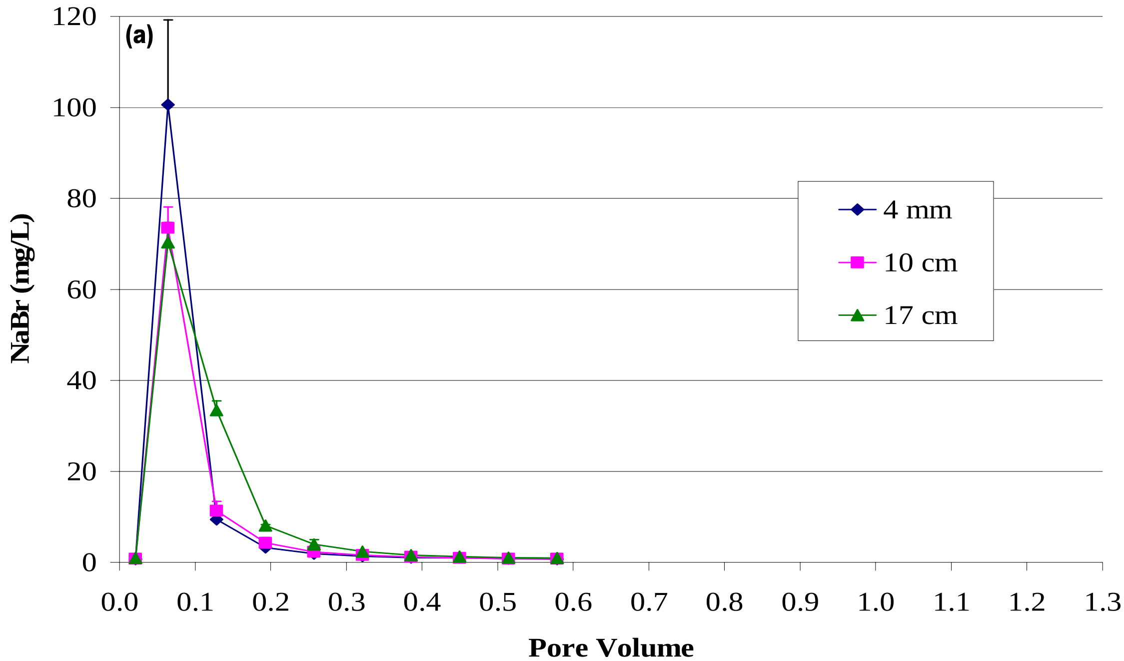


Figure 3-3. NaBr concentrations at various depths measured at (a) front, (b) middle, and (c) end for a continuous hydraulic loading of 7.6 L/min following addition of a bromide tracer to the inlet. Bars show one standard deviation.

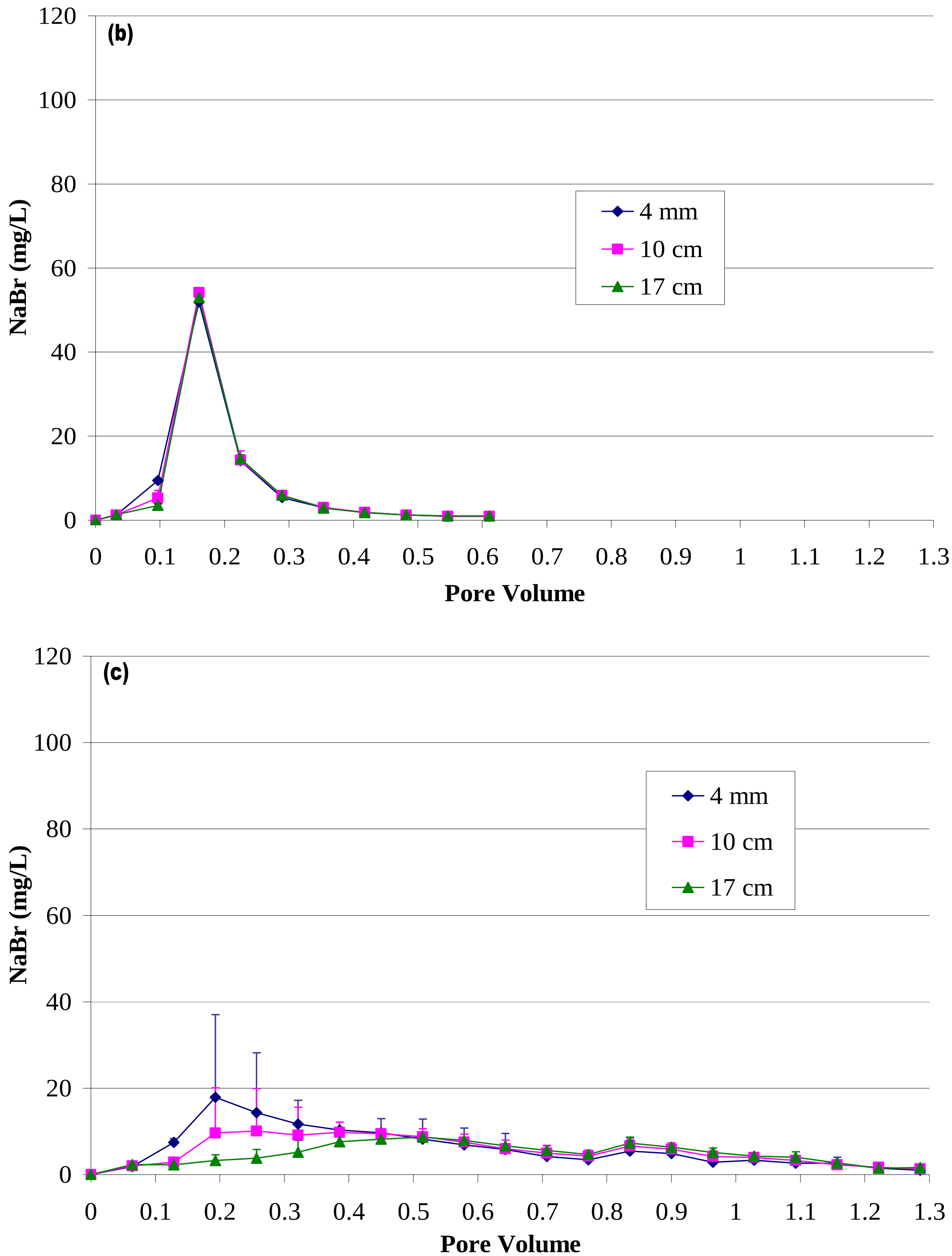


Figure 3-3. (continued).

As with the 3.8 L/min loading rate; all depths had peak concentrations after 0.6 pore volumes at the first row of sampling ports. In contrast to the lower loading rate, the highest concentration at this row of ports was at the shallowest level, but was the lowest concentration at the previous flow. This may have to do with the approach taken in adding the tracer. With the first experiment there was a delay in following the tracer with tap water. This resulted in the tracer being loaded as a dose load rather than in a continuous flow. This was corrected in the second tracer experiment where the tracer was almost immediately followed by the constant flow of tap water. The peak at the midpoint was after 0.16 pore volumes which is more than twice what occurred in the first experiment. There was no difference in concentrations with depth at this point indicating the water was evenly mixed by the midpoint. Once again, by the end of the SFCW, peak concentrations are varied with depth not only in magnitude but also in pore volumes passed. Peaks occurred after 0.19, 0.26, and 0.51 pore volumes for the shallow, middle and deep sampling ports respectively. Other than the deepest ports, the peaks occurred after fewer pore volumes than when the water was being loaded at 3.8 L/min. As with the slower flow rate, the highest peak at the end was at the top of the wetland and most of the tracer had passed through the wetland after 1.3 pore volumes.

Discussion

In comparing the breakthrough curves developed in this study with those generated in Stecher and Weaver (2003) and Weaver et al. (2003), it appears as if loading a wetland with a constant hydraulic rate impacted water distribution within the wetland. Stecher and Weaver (2003) showed that a Br^- tracer in the same wetland cell loaded in a batch fashion takes 2 pore volumes to move completely through. The tracer moved through the wetland more than twice as quickly when constantly loaded. The variation in tracer concentration with depth demonstrates that not only was the water not well mixed, but was also far from being plug flow. Because the water moved through the wetland quickly, but did not achieve plug flow, most of the water is moving through bypass flow. SFCW which flow is dominated by bypass flow often fail to perform as well as those with uniform flow distribution.

Although it is rare for a wetland to receive one pore volume worth of water in one dosing, the rates at which the water was loaded were not unrealistic. SFCW which are gravity fed without any type of flow equalization, are often loaded in a manner similar to our study. During times of high water use, for example when the washing machine is running, a wetland may receive a load similar to those used here. In addition to possible impact from a shortened hydraulic retention time, during times of high water use the wetland may experience bypass flow which may result in lower treatment effectiveness.

This study indicates that the method of dosing, gravity versus equal dosings, impacts the flow pattern in the wetland. The rate at which the water flows in has a small effect on water distribution as well. Further investigation could be done to investigate an optimal flow rate as well as examine the differences between batch and gravity loading.

CHAPTER IV

EVALUATION OF EFFECT OF HEADER DESIGN ON WASTEWATER TREATMENT

Introduction

The main objectives in header design for subsurface flow constructed wetlands (SFCW) are minimizing short-circuiting and clogging while maximizing even flow distribution. In systems with very large widths, or small aspect ratios, special care should be taken to ensure the header spans the entire width of the SFCW and distributes water evenly across that span (USEPA, 2000a). An array of header designs exists including: perforated or slotted manifolds, leaching chambers, a series of reducing tees or 90 degree elbows that can be rotated on the header, or a system of multiple inlets using weirs (Cooper and Hobson, 1989 and USEPA, 2000a). Leaching chambers are probably the newest of all the methods. Their use was brought into practice to address concerns of potential clogging due to the high concentration of organic material settling in the front of the wetland. Traditionally used in drainfields, the chambers are thought to have the advantage of providing a place for organic material to collect when entering the wetland. To date there have not been published evaluations of the effectiveness of the leaching chamber to meet the header design objectives.

Six gravel filled wetlands in Texas with leaching chamber headers (Richter and Weaver, 2003) generally provided less than 80% BOD_5 reduction but headers of a different design provided treatment of better than 85% (Nerella et al., 2002). The goal of this study was to examine the impact of header selection on wetland treatment effectiveness.

Methods and Materials

Field Work

Two activities were conducted in this investigation. First, bromide was used as a tracer to follow the uniformity of water flowing through four wetlands using leaching chambers as headers. Second, the header at one wetland was replaced to determine if that would improve wastewater treatment. The majority of the study was conducted at Site 1, a SFCW in Nacogdoches, Texas, which treated domestic wastewater from a five bedroom home using water conserving fixtures. The water entering the wetland was pretreated by passing through two 1.89 m^3 septic tanks. The average water use for the home was 0.50±0.12 m^3/d. The average effluent BOD_5 concentration from the home septic tank was 171.8±45.0 mg/L.

To determine if changing inlet devices impacted effluent quality at this site, influent and effluent samples were collected prior to and following the exchange of the header. A two-week period was allowed before effluent samples were collected to allow materials that were disturbed during removal of the leaching chamber to settle. Samples of 500 ml were collected from a port in the influent end of the wetland as well as from inside the outlet device using a hand pump. The temperature of the samples were recorded and then the samples were put on ice to be transported back to the Texas A&M Soil Microbiology lab for water quality analysis.

Figures 4-1 through 4-3 detail use of a leaching chamber as a header at Site 1. The width of the leaching chamber was only 2.0 m which is 2.3 m shorter than the width of the SFCW at Site 1 and 1.1 m shorter than the widths of SFCW at Sites 2, 3 and 4.

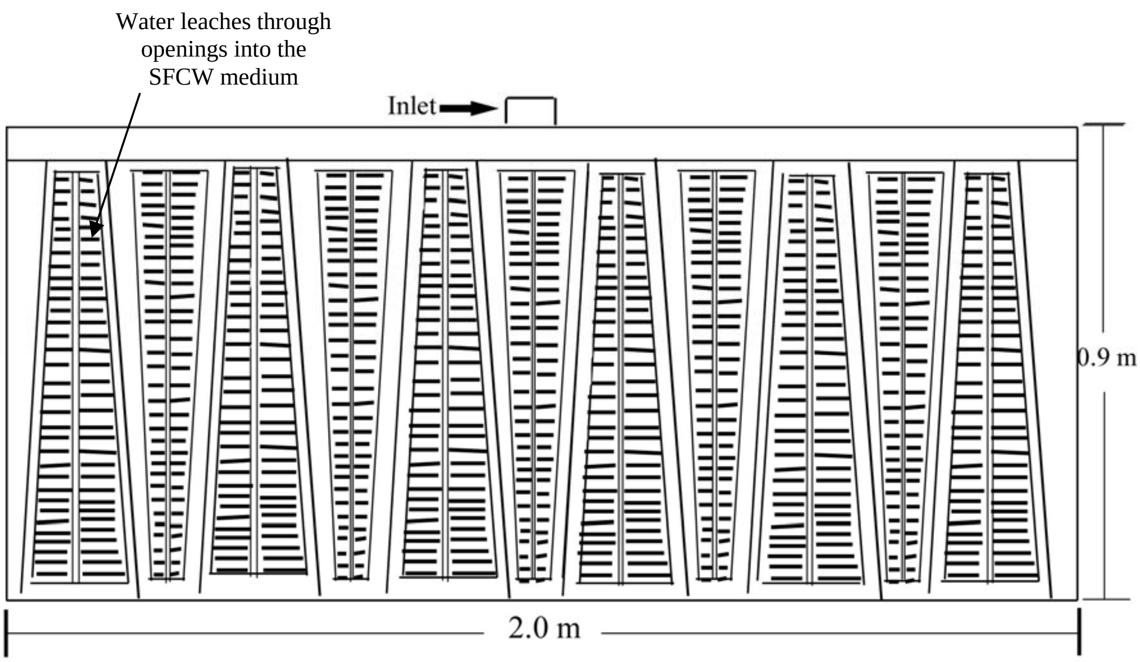


Figure 4-1. Front view of the leaching chamber used as a header at Sites 1,2,3 and 4.

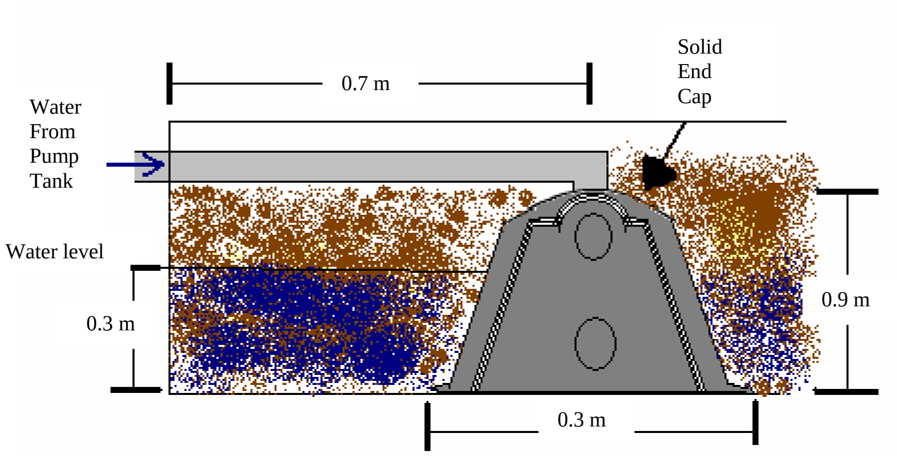


Figure 4-2. Cross sectional view along the length of the SFCW using a leaching chamber as a header at Site 1. (Not to scale)

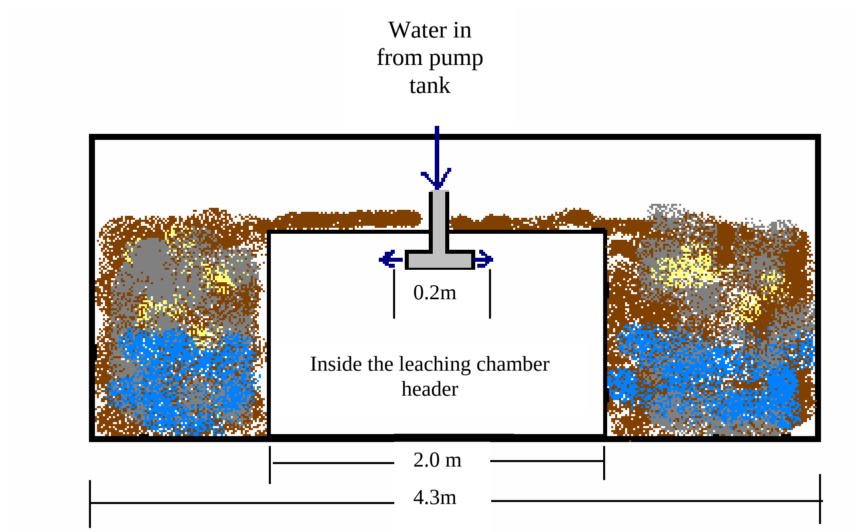


Figure 4-3. Cross sectional view across the width of the SFCW using a leaching chamber as a header at Site 1. (Not to scale)

It was hypothesized that any differences in treatment between the two headers would be due to water distribution. Prior to the header switch, a bromide tracer study was conducted at Site 1 as well as three other systems using leaching chambers as headers in SFCW treating residential septic tank effluent. Site 2 was located in

Nacogdoches, Site 3 was in Dayton, Texas, and Site 4 was in Point Blank, Texas. The tracer studies were used to examine typical flow through a wetland loaded with a leaching chamber. A description of the tracer study sites is given in table 4-1.

Table 4-1. Experiment sites and flow study details

Site #	**Dimensions LXW (mXm)**	**Method of dispersal**	**Loading Method**	**Avg Hydraulic Load (m^3/d)**	**Avg Influent BOD (mg/l)**	**Pore Volume (m^3)**	**Number of doses used in tracer study**
1	8.5 X 4.3	Drain field	Pump	0.50 ± 0.12[a]	171 ± 40	3.2	16
2	11.0 X 3.1	Drain field	Gravity	0.85 ± 0.41	179 ± 45	2.9	17
3	9.1 X 3.1	Spray	Gravity	1.37 ± 0.61	208 ± 40	2.4	15
4	8.2 X 3.1	Spray	Gravity	0.66 ± 0.21	73 ± 28	2.2	12

[a] Averages shown with ± one standard deviation

The sampling port scheme is shown in figure 4-4 for Sites 1 and 2 and figure 4-5 for Sites 3 and 4. The sampling ports for the study were 1 cm inside diameter chlorinated polyvinyl chloride (CPVC) pipe. The pipe was tapered at the end and had two 3 mm holes drilled about 1 cm from where the tapering began. Samples were collected using an 8 mm outside diameter flexible plastic tube connected to a 60 ml syringe. Before a particular port was sampled, one full syringe volume was drawn and then discarded. A second syringe volume was filled and then placed into a 120 mL plastic collection cup. This method of discarding the first water drawn and then keeping the second sample was used to ensure any standing water trapped in the sampling port was not taken as the sample. All samples were brought back to the lab to be analyzed using a Br^- selective electrode (Orion 9435, Beverly, MA)

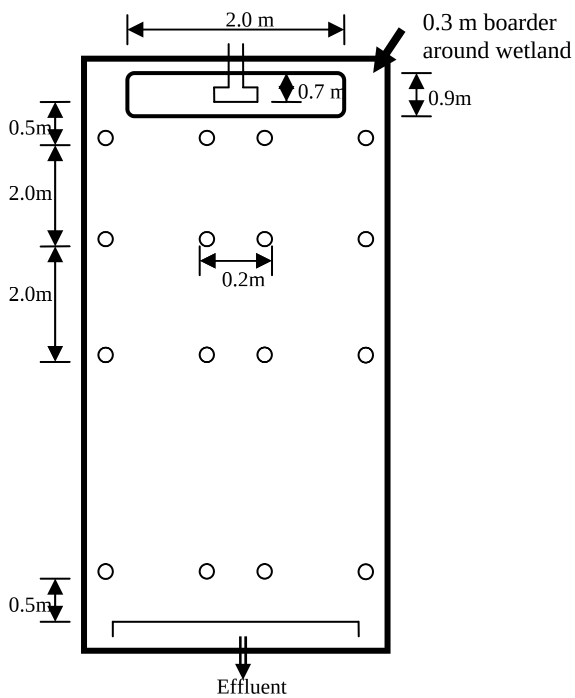


Figure 4-4. Sampling port scheme for Sites 1 and 2.

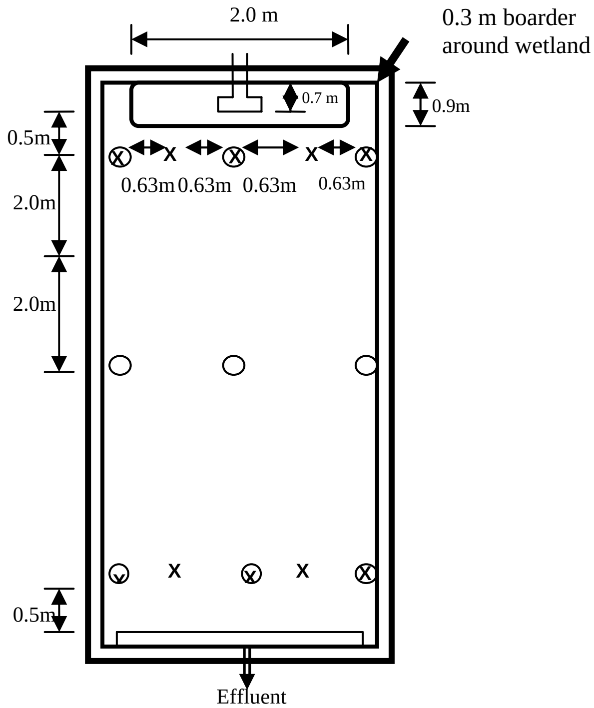


Figure 4-5. Sampling port scheme for Sites 3 (O) and 4 (X).

Bromide was selected as a tracer because it is inexpensive, flows with water without retardation, is nontoxic at relatively low levels, and is easily measured. The tracer consisted of 9 grams of NaBr mixed into 23 L of tap water. The mixture was drained into the inlet line just upstream of where the influent pipe teed into the header. A dose of 166 L of tap water followed immediately after the tracer was introduced to complete a full 189 L load. Samples were taken without delay from the two rows of sampling ports closest to the header and then again after the 189 L dose was completed. During each dosing, and for two to three minutes after dosing, an increase in hydraulic head occurred near the SFCW header, thus a 10-minute stabilization period was allowed permitting SFCW hydraulics to reach equilibrium before subsequent dosing. Each sequential dose was 189 L of tap water flowing at a rate of 12 L/min. The dose volume and rate were monitored at every dosing with a stopwatch and a flow meter tied into the line. After the dosing, samples were collected from relevant ports. This pattern of dosing, sampling and allowing the water to stabilize continued until approximately one pore volume had passed through the wetland. The pore volume was calculated by multiplying the length, width, water depth and porosity of the media. The design depth for all systems was 27 cm and the porosity was assumed to be 32%. Because of variations in the size of each wetland, there was some variation in the number of doses required to achieve one pore volume (table 4-1).

To determine if the leaching chamber header design was impacting treatment of wastewater in the SFCW, the leaching chamber was removed from the wetland at Site 1 and replaced with a perforated manifold. This particular inlet device was selected because it has been shown to be an effective header design (USEPA, 2000a and Stecher and Weaver, 2003). The new header consisted of two length of 3.18 cm diameter schedule 40 PVC pipe, each 2 m long, fitted into a tee connected to the line coming from a pump tank. Two 0.4 cm holes were drilled in the pipe every 15 cm along the length of the pipe. The header was placed so that the lower set of holes sat right above the level of water but also so the header was still covered in gravel. The placement of the pipe met the suggestion of USEPA (1993b) to have the pipe at or above the water level, while attempting to mitigate potential odor by not having the water discharge over the surface of the wetland. During the installation process, before the new header was covered, the pump was turned on to observe distribution across the width of the header. The orifices in the header all appeared to be discharging similar amounts of water. The new header was covered with the media that was moved from around the leaching chamber.

Lab Work

All samples were analyzed with a Br^- selective electrode in the lab and mV readings were calibrated to known concentrations of Br^-. Known concentrations (1, 2, 5, 10, 20, 50, and 100 ppm) of NaBr in tap water from each site were used for calibration. The probe was recalibrated using the described methods approximately every 60 samples to avoid error due to drift of the probe. Calibration curves are shown in appendix C.

All wastewater samples were analyzed for water quality using standard methods (APHA, 1995). The analysis included #5210B for BOD_5, #2540 D & E for total suspended solid (TSS) and volatile suspended solids (VSS), ammonium nitrogen #4500 E, and P--#4500 E for phosphorus.

Results

The results for the tracer study for Site 1 are shown in figure 4-6. By examining the graphs in figure 4-6, it is evident that the header failed to achieve equal flow distribution across the width of the wetland. The concentrations peaked in the middle sampling ports following fewer loadings than those on the edges of the wetland. This indicates that the water was moving through the middle of the wetland more quickly than along the sides. The peak concentrations vary in magnitude as well as occurrence with pore volume load. The only patterns without the deviating peaks are the two middle peaks. At the front of the wetland the left side (looking down the length of the wetland from the header) received the most tracer out of the four ports (fig. 4-6a). In addition, aside from a small increase at the second sampling ports (fig. 4-6b), the left side decreased in concentration more rapidly than at the other three widths (fig. 4-6c&d). An interesting point to note is that most of the tracer had passed through the wetland in one pore volume if we assume the breakthrough peaks were symmetrical.

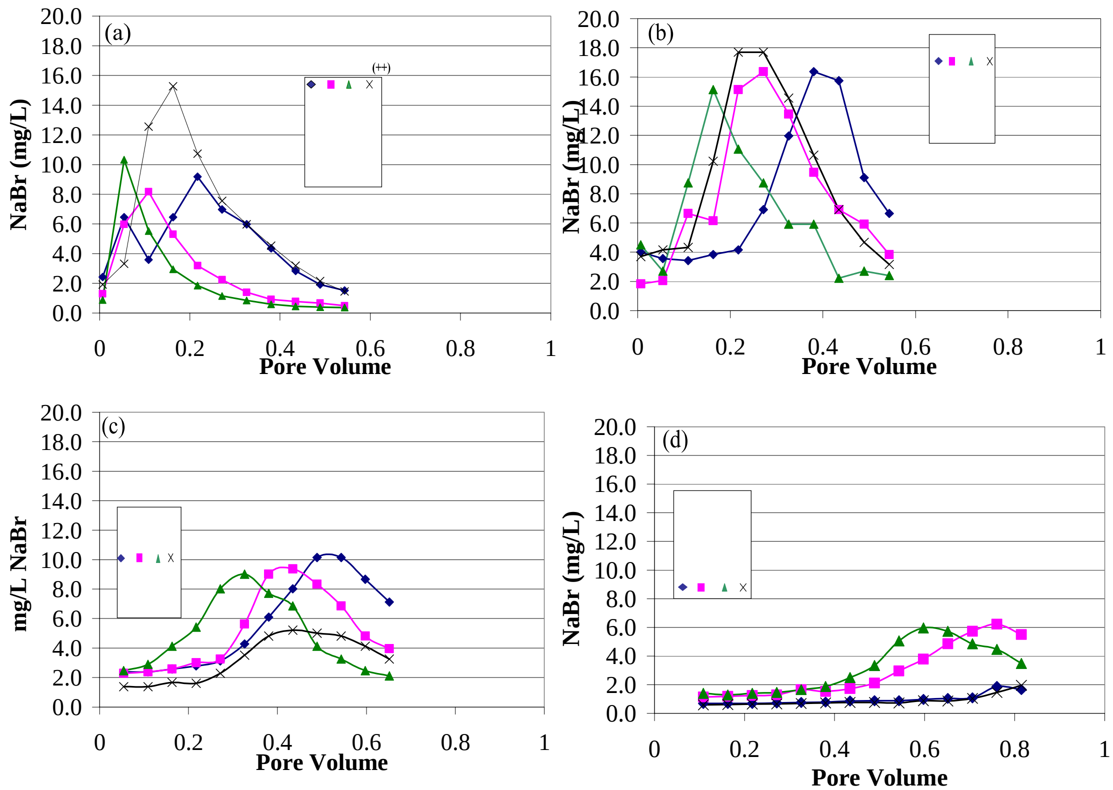


Figure 4-6. Breakthrough curves for bromide following addition of bromide tracer to the front of the wetland at Site 1 and following with a flush of water;(a) first row of sampling ports, (b) second row of sampling ports, (c) third row of sampling ports and (d) last row. (++) Legend showing position of port in the wetland.

The tracer study results from the three other wetlands fed through leaching chambers returned very similar results to those observed at the Site 1. All sites failed to demonstrate equal flow distribution.

Similar to the trend from Site 1, the graphs for Site 2 do not demonstrate equal flow across the width of the wetland (fig. 4-7). Once again, the peaks were variable with width; the left side having the highest peak. In this situation water moved very rapidly down the length of the wetland, except along the right side.

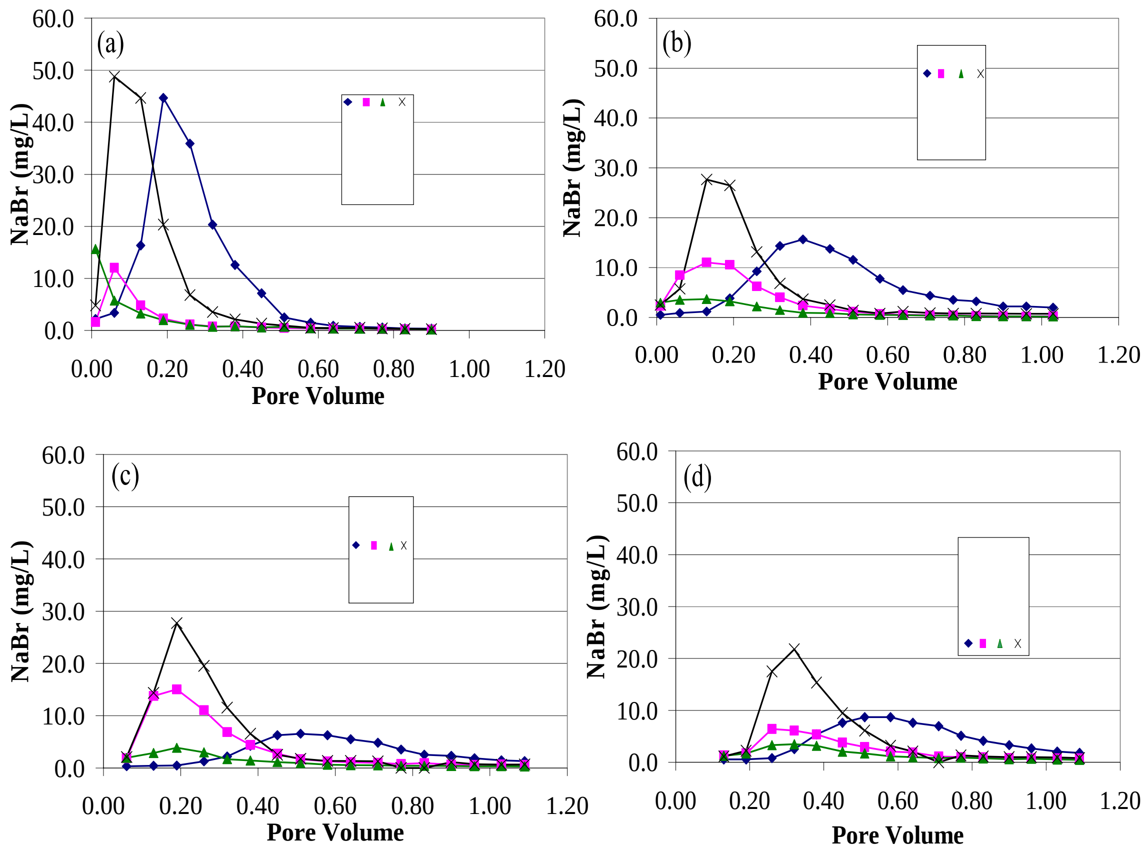


Figure 4-7. Breakthrough curves for bromide following addition of bromide tracer to the front of the wetland at Site 2 and following with a flush of water; (a) first row of sampling ports, (b) second row of sampling ports, (c) third row of sampling ports and (d) last row.

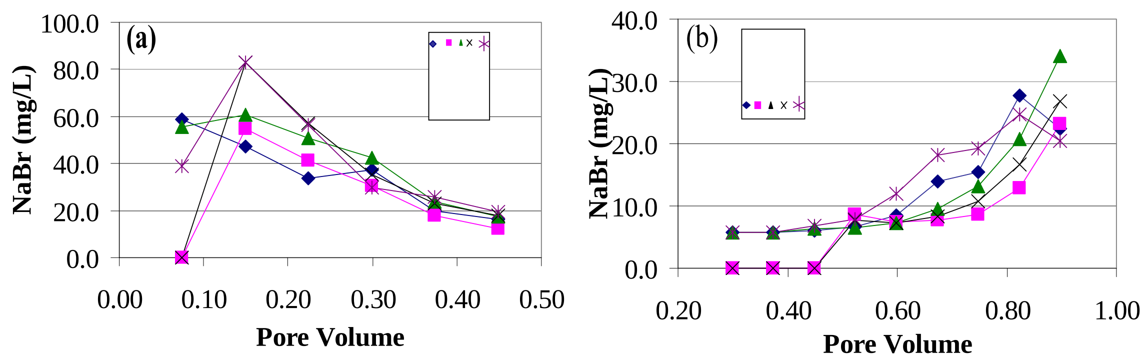


Figure 4-8. Breakthrough curves for bromide following addition of bromide tracer to the front of the wetland at Site 3 and following with a flush of water; (a) first row of sampling ports and (b) second row of sampling ports.

The results at Site 3 (fig. 4-8) demonstrate irregularity in the flow across the width of the wetland. The highest concentrations at the front of the wetland occur on the left side. Unlike the first two sites, the timing of the peak occurrence is consistent along the width and length, although the rates at which the tracer lowers in the front and builds at the end with each pumping is variable.

Site 4 fails to demonstrate flow equalization as well (fig. 4-9). The peaks vary greatly in size, and slightly in occurrence at each port. In addition, there is great variability in the rates at which the tracer moves past the sampling ports across the width.

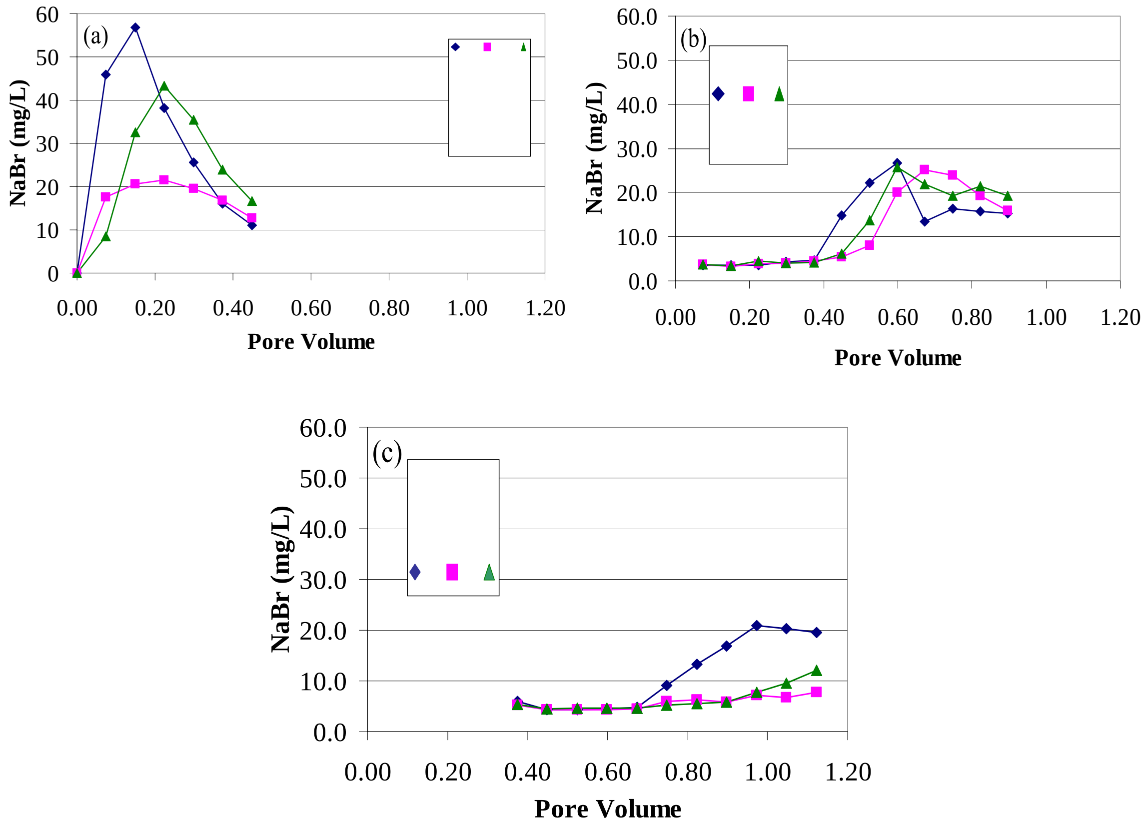


Figure 4-9. Breakthrough curves for bromide following addition of bromide tracer to the front of the wetland at Site 4 and following with a flush of water; (a) the front of the wetland, (b) second row of sampling ports and (c) end of the wetland.

Figure 4-10 shows BOD_5 effluent values for the period of time just before and two weeks after the header change at Site 1. The average effluent BOD_5 concentration for the leaching chamber header was 41.8 ± 12.4 mg/L. After the perforated manifold was installed, the average effluent value decreased to 17.1 ± 6.4 mg/L. After the second week of sampling, the wetland was able to consistently achieve secondary water quality.

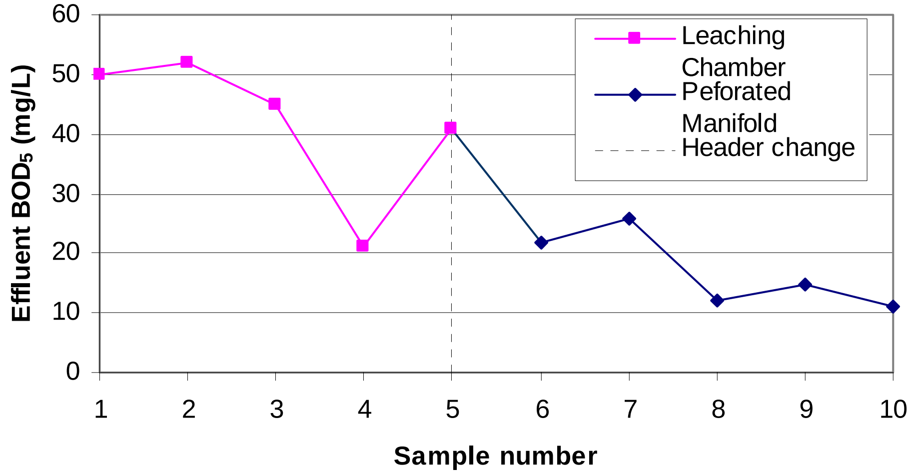


Figure 4-10. Effluent BOD_5 values from Site 1 collected right before and two weeks after changing the header from a leaching chamber to perforated manifold.

Effluent samples collected after the header change were also evaluated for ammonium-nitrogen, TSS, VSS, and phosphorus. The average effluent concentrations following header replacement were compared to historical water quality data from the site. A Student's-t test was performed for each water quality parameter to determine if there was a significant difference between effluent values before and after the switch. The results from this analysis are shown in table 4-2.

Further water quality analysis established that not only was BOD_5 treatment improved, but there was also an improvement in phosphorus, TSS, and VSS treatment. The reduction in VSS is expected to accompany a reduction in TSS since TSS and VSS are closely related. In addition, if more uniform flow was achieved, the water would have more interaction with the media and allow more phosphorus to precipitate out.

Table 4-2. Comparison of NH_4, P, TSS, and VSS effluent values from a leaching chamber header and perforated manifold header at Site 1.

	Nitrogen (mg/L)	Phosphorus (mg/L)	TSS (mg/L)	VSS (mg/L)
Leaching Chamber	23.9±10.7[a]	4.5±1.4	17.8±7.1	14.5±4.9
Perforated Manifold	18.6±1.1	2.9±0.3	7.5±4.9	5.3±3.2
P value	.11	.007	.004	<.001

[a]Averages shown with ± one standard deviation

Discussion

Both components of this study indicate that inlet device did indeed have an impact on the overall performance of a wetland. If an inlet device fails to meet USEPA's (2000a) design objectives for headers, then the treatment effectiveness of the system may be compromised. Stecher and Weaver (2003) conducted bromide tracer studies very similar to those described in this study but on wetlands loaded through a perforated manifold. Not only did the tracer study show that the header was able to achieve equal flow distribution at a number of different loading regiments, but most of the tracer took two pore volumes to leave the wetland. More rapid movement of the tracer observed in this study may indicate that the leaching chamber is causing preferential flow such that water moves through the wetland at twice the rate it should.

The use of leaching chambers as SFCW headers is a recent practice and extensive study on their effectiveness has not yet been pursued. The results of this study indicate that, when implemented as in the wetlands studies, they do not meet the requirements of an effective header.

CHAPTER V

SUMMARY AND CONCLUSIONS

The objective of this study was to determine if specific design parameters, such as aspect ratio, flow rate and header design have an impact on flow distribution and treatment of BOD_5 provided by a SFCW. The influence of aspect ratio was examined by comparing BOD_5 percent removal in a wetland with a 1:1 aspect ratio to that from a wetland with a 4:1 aspect ratio. Flow studies were also used to evaluate the effect of continuous loading at two flow rates on flow patterns through the wetland. The effect of header design was observed through flow studies as well as through comparing water treatment provided by the same wetland loaded through a leaching chamber then through a perforated manifold. Through this research, valuable insight was gained about the mechanisms affecting BOD_5 removal.

What has previously been assumed to be true about the impact of aspect ratio on treatment efficiency was based on theory or studies conducted on wetlands that are not representative of those used in residential settings. The results of this study demonstrated that, although previously assumed to have little or no impact (Bounds et al. 1998), increasing aspect ratio improved treatment effectiveness. Further inspection of the data also revealed that, although the organic load into the system effected BOD_5 removal, the hydraulic loading also impacted treatment effectiveness.

In further investigation of hydraulic loading, it was discovered by comparing tracer breakthrough curves from a constant flow of 3.8 L/min to 7.6 L/min, that hydraulic flow rate had a small impact on proper flow distribution. There was variation in how many pore volumes the water took to pass through the middle of the wetland, but no difference in the number of pore volumes needed for the tracer to move through the entire wetland. In addition to effects observed with varying flow rate, comparisons to tracer studies conducted simulating batch loading indicate that the method of dosing influenced the water distribution.

Equal flow distribution was found to be vital in improving effluent water quality in the experiment examining header design. Tracer studies demonstrated that leaching chambers used as headers at the sites studied were not able to achieve equal flow distribution. After changing the header at one site, a dramatic improvement in effluent quality was achieved.

This research study on a whole demonstrated the importance of equal flow distribution in improving BOD_5 removal efficiency as well as the way a variety of parameters can influence flow distribution. Careful consideration should be given to selecting aspect ratio, flow rate, method of loading, and header design used in a wetland. As understanding of individual design parameters increases, design of SFCW for on-site treatment of domestic wastewater can be enhanced. Enhanced treatment by on-site technologies results in lower discharge of contaminants into the environment which will help reduce the pollution threat to our limited fresh water supplies.

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APPENDIX A

Table A-1. Experiment 1 (low organic loading) hydraulic loading, influent and effluent BOD_5 values and influent and effluent organic loading values collected from cells 1 and 2 when half of the water was sent down both sides of the wetland (1:1 aspect ratio), and from cells 3 and 4 when most of the water went down one side (4:1).

	Sampling Date	Flow (m^3/d) Left****	Right	Influent BOD_5 (mg/L)	Effluent BOD_5 (mg/L) Left	Right	Effluent Load ($gm^{-2}d^{-1}$) Left	Right	Influent Load* ($gm^{-2}d^{-1}$) Left	Right
	8/8	0.23	0.30	52.9	23.1	39.8	0.51	1.15	1.17	1.53
	8/13	0.57	0.90	31.1	9.5	12.5	0.53	1.08	1.72	2.70
	8/14	0.18	0.46	68.3	19.7	26.3	0.34	1.16	1.16	3.02
	8/20	0.20	0.46	126.2	14.9	17.2	0.28	0.76	2.37	5.58
	8/21	0.11	0.46	74.3	5.8	15.5	0.06	0.69	0.81	3.29
1:1 ratio**	8/27	0.43	0.33	61.9	17.8	23.8	0.74	0.77	2.58	1.99
	8/28	0.37	0.29	50	13.7	17.4	0.49	0.48	1.78	1.38
	8/29	0.30	0.24	58.2	6.9	7.2	0.20	0.17	1.70	1.33
	9/10	0.25	0.37	72	23.3	37.3	0.56	1.31	1.72	2.53
	9/12	0.22	0.27	54.4	20.2	8.3	0.42	0.21	1.13	1.40
	9/18	0.17	0.21	136.2[†]	17.5	32	0.29	0.64	2.23	2.71
	9/19	0.62	0.89	77.9	14	16.3	0.83	1.40	4.63	6.69
	10/13	0.63	0.58	117	18	17.4	1.10	0.98	7.14	6.56
	10/15	0.47	0.45	70.7	8.6	14.8	0.39	0.64	3.17	3.04
	10/17	0.36	0.34	54.6	6.9	14.7	0.24	0.48	1.89	1.78
	9/3	0.25	0.07	91.8	8.0		0.10		1.10	
	9/4	1.14	0.28	85.5	11.3		0.62		4.69	
	9/5	0.26	0.07	103.2	4.7		0.06		1.27	
	10/20	1.07	0.00	127	10.7		0.55		6.53	
	10/22	0.90	0.07	64.4	5.5		0.24		2.79	
	10/24	0.85	0.07	72	5.2		0.21		2.95	
	10/25	1.01	0.10	125.0	10.7		0.52		6.08	
	10/30	0.86	0.07	36.5	6.3		0.26		1.50	
	11/1	0.98	0.07	78.9	3.6		0.17		3.73	
4:1 ratio***	11/5	0.57	0.04	93.1	11.0		0.30		2.54	
	11/10	0.83	0.07	50.9	5.9		0.24		2.04	
	11/15	0.73	0.21	43.7	8.1		0.28		1.53	
	11/19	0.80	0.24	83.0	1.4		0.05		3.19	
	11/26	0.75	0.22	76.1	1.4		0.05		2.73	
	12/1	0.42	0.21	46.5	1.4		0.03		0.94	
	12/3	0.78	0.21	60.6	2.8		0.10		2.26	
	12/12	0.74	0.21	64.8	0.6		0.02		2.29	
	12/16	0.70	0.21	59.2	2.2		0.07		2.00	
	1/12	1.17	0.00	87.4	4.5		0.25		4.90	
	1/13	0.76	0.00	81.7	3.4		0.12		2.99	
	3/17	0.24	0.00	116[†]	4.8		0.06		1.36	
	3/26	0.52	0.03	116[†]	2.8		0.07		2.87	
	3/30	0.55	0.03	116[†]	2.8		0.07		3.07	

* Calculations of organic load are based on a 20.8 m^2 surface area.

** BOD effluent values for cells 3 and 4 are found in table A-4 by sampling date

*** BOD effluent values for cells 1 and 2 are found in table A-5 by sampling date

**** "Left" correspond to cells 1 and 3, "Right" corresponds to cells 2 and 4

[†] Outlier value not used in average concentration calculations

Table A-2. Experiment 2 (medium organic loading) hydraulic loading, influent and effluent BOD_5 values and influent and effluent organic loading values collected from cells 1 and 2 when half of the water was sent down both side of the wetland (1:1 aspect ratio), and from cells 3 and 4 when most of the water went down one side (4:1).

	Sampling Date	Flow (m^3/d) Left****	Right	Influent BOD_5 (mg/L)	Effluent BOD_5 (mg/L) Left	Right	Effluent Load ($gm^{-2}d^{-1}$) Left	Right	Influent Load* ($gm^{-2}d^{-1}$) Left	Right
1:1 ratio**	9/8	0.72	0.82	103.0	12.9	22.5	0.90	1.78	7.18	8.16
	9/23	0.76	0.34	90.2	18.8	20.8	1.37	0.69	6.55	2.99
	9/24	0.82	0.62	70.7	23.6	19.2	1.86	1.15	5.57	4.23
	9/30	0.65	0.60	98.6	24.4	21.1	1.52	1.22	6.15	5.72
4:1 ratio***	10/7	1.13	0.35	118	9.3		0.50		6.40	
	10/8	1.04	0.32	146.9†	14.7		0.74		7.38	
	10/21	0.82	0.22	74.4	3.3		0.13		2.93	
	10/22	0.83	0.25	134.1	12.3		0.49		5.36	
	10/25	1.13	0.33	106	10.1		0.55		5.75	
	11/1	0.00	1.69	95.8		17.4		1.41		7.78
	11/2	0.00	1.36	101		17.1		1.12		6.60
	11/3	0.06	1.34	101.0		14.3		0.92		6.51
	11/4	0.05	0.78	94.7		14.3		0.54		3.57
	11/5	0.09	1.33	113.1		19.6		1.25		7.22
	11/8	0.09	1.29	104		15.7		0.97		6.44
	11/9	0.11	1.67	103		8.1		0.65		8.29
	11/10	0.06	0.89	112.0		15.0		0.64		4.82

* Calculations of organic load are based on a 20.8 m^2 surface area

** BOD_5 effluent values for cells 3 and 4 are found in table A-4 by sampling date

*** BOD_5 effluent values for cells 1 and 2 are found in table A-5 by sampling date

**** "Left" correspond to cells 1 and 3, "Right" corresponds to cells 2 and 4

† Value not used in calculations because it was more than two standard deviations from the mean

Table A-3. Experiment 3 (high organic loading) hydraulic loading, influent and effluent BOD_5 values and influent and effluent organic loading values collected from cells 1 and 2 when half of the water was sent down each side of the wetland (1:1 aspect ratio), and from cells 3 and 4 when most of the water went down one side (4:1).

	Sampling Date	Flow (m^3/d)		Effluent BOD_5 (mg/L)		Influent BOD_5 (mg/L)	Effluent Load ($gm^{-2}d^{-1}$)		Influent Load* ($gm^{-2}d^{-1}$)	
		Left****	Right	Left	Right		Left	Right	Left	Right
1:1 ratio**	11/15	0.58	0.83	51.0	53.4	148.5	2.75	4.15	8.00	11.53
	11/16	0.46	0.67	26.6	29.4	110	1.14	1.85	4.73	6.92
	11/17	0.53	0.76	33.9	28.3	132.2	1.70	2.01	6.61	9.41
	11/18	0.77	1.08	17.4	26.0	100.5	1.26	2.63	7.27	10.16
	12/7	0.44	0.74	39.0	20.3	169.0	1.62	1.41	7.04	11.75
	12/8	0.58	0.76	36.5	31.0	120.3	1.97	2.21	6.50	8.56
4:1 ratio***	12/17	1.15	0.00	16		141.0	0.85		7.47	
	12/14	1.76	0.00	22.2		189.0	1.81		15.38	
	12/15	1.09	0.00	37.9		145.2	1.91		7.30	
	12/16	0.95	0.00	24.8		131.0	1.09		5.77	
	12/13	0.79	0.38	22.3		122.1	0.81		4.43	
	11/29	0.00	1.71		15.7	148		1.24		11.71
	11/30	0.14	1.09		12.1	138.9		0.61		6.96
	12/1	0.18	1.24		9.5	196		0.54		11.21
	12/2	0.14	1.24		16.2	150.3		0.93		8.60
	12/3	0.16	1.24		7.6	139.4		0.43		7.97

*** Calculations of organic load are based on a 21.5 m^2 surface area.**

**** BOD_5 effluent values for cells 3 and 4 are found in table A-4 by sampling date**

***** BOD_5 effluent values for cells 1 and 2 are found in table A-5 by sampling date**

**** "Left" corresponds to cells 1 and 3; "Right" corresponds to cells 2 and 4

Table A-4. Hydraulic loading and influent and effluent BOD_5 values from cells 3 and 4 when water was sent equally down both sides of the wetland.

	Sampling Date	Flow (m^3/d) 3	Flow (m^3/d) 4	Effluent BOD (mg/L) 3	Effluent BOD (mg/L) 4	Influent BOD (mg/L)
Experiment 1[(a)]	8/8	0.23	0.30	11.3	9.2	52.9
	8/13	0.57	0.90	1.1	4.4	31.1
	8/14	0.18	0.46	5.4	6.2	68.3
	8/20	0.20	0.46	6.5	9.0	126.2
	8/21	0.11	0.46	3.7	10.2	74.3
	8/27	0.43	0.33	3.3	5.8	61.9
	8/28	0.37	0.29	3.7	5.6	50
	8/29	0.30	0.24	2.7	4.6	58.2
	9/10	0.25	0.37	5.8	8.5	72
	9/12	0.22	0.27	6.2	5	54.4
	9/18	0.17	0.21	12	11.8	136.2
	9/19	0.62	0.89	7	5	77.9
	10/13	0.63	0.58	10.4	5.1	117
	10/15	0.47	0.45	7.3	5.3	70.7
	10/17	0.36	0.34	6.1	7.6	54.6
Experiment 2[(b)]	9/8	0.72	0.82	9.5	4.2	103.0
	9/23	0.76	0.34	9.5	8.7	90.2
	9/24	0.82	0.62	13.2	8.0	70.7
	9/30	0.65	0.60	8.4	9.0	98.6
Experiment 3[(c)]	11/15	0.58	0.83	14.9	21.1	148.5
	11/16	0.46	0.67	5.1	9.3	110
	11/17	0.53	0.76	9.5	13.0	132.2
	11/18	0.77	1.08	12.3	7.4	100.5
	12/7	0.44	0.74	10.7	2.5	169.0
	12/8	0.58	0.76	17.1	8.9	120.3

[(a)] Aspect ratio test with the wetland treating water directly from one duplex
[(b)] Aspect ratio test with water from two duplexes being treated
[(c)]Aspect ratio test with water from two duplexes and dog food added being treated by the wetland

Table A-5. Hydraulic loading and influent and effluent BOD_5 values from cells 1 and 2 when water was sent down one side or the other according to sampling date.

	Sampling Date	Flow (m^3/d) 1	2	Effluent BOD (mg/L) 1	2	Influent BOD (mg/L)
Experiment 1[(a)]	9/3	0.25	0.07	26.5		91.8
	9/4	1.14	0.28	31.9		85.5
	9/5	0.26	0.07	12.2		103.2
	10/20	1.07	0.00	29.5		127
	10/22	0.90	0.07	17.1		64.4
	10/24	0.85	0.07	14		72
	10/25	1.01	0.10	29.5		125.0
	10/30	0.85	0.07	11.6		36.5
	11/1	0.98	0.07	21.3		78.9
	11/5	0.57	0.04	19.4		93.1
	11/10	0.83	0.07	14.9		50.9
	11/15	0.73	0.21	13.8		43.7
	11/19	0.80	0.24	17.0		83.0
	11/26	0.74	0.22	7.0		76.1
	12/1	0.42	0.21	14		46.5
	12/3	0.77	0.21	9.5		60.6
	12/12	0.73	0.21	20.5		64.8
	12/16	0.70	0.21	9.8		59.2
	1/12	1.17	0.00	10.9		87.4
	1/13	0.76	0.00	14.9		81.7
	3/17	0.24	0.00	53.9		116
	3/26	0.51	0.03	52.5		116
	3/30	0.55	0.03	51.1		116
Experiment 2[(b)]	10/7	1.13	0.35		35.9	118
	10/8	1.04	0.32		52.3	146.9
	10/21	0.82	0.22		16.3	74.4
	10/22	0.83	0.25		48.4	134.1
	10/25	1.13	0.33		26.7	106
	11/1	0.00	1.69	50.3		95.8
	11/2	0.00	1.36	44.9		101
	11/3	0.06	1.34	44.6		101.0
	11/4	0.05	0.78	39.5		94.7
	11/5	0.09	1.33	51.9		113.1
	11/8	0.09	1.29	39.6		104
	11/9	0.11	1.67	63.9		103
	11/10	0.06	0.89	59.0		112.0
Experiment 3[(c)]	12/13	0.79	0.38	46.1		141.0
	12/14	1.76	0.00	82.5		189.0
	12/15	1.09	0.00	77.1		145.2
	12/16	0.95	0.00	69.9		131.0
	12/17	1.15	0.00	64.7		122.1
	11/29	0.00	1.71		34.5	148
	11/30	0.14	1.09		40.2	138.9
	12/1	0.18	1.24		46.9	196
	12/2	0.14	1.24		59.5	150.3
	12/3	0.16	1.24		56.9	139.4

[(a)] Aspect ratio test with the wetland treating water directly from one duplex
[(b)] Aspect ratio test with water from two duplexes being treated
[(c)] Aspect ratio test with water from two duplexes and dog food added being treated by the wetland

APPENDIX B

Table B-1. Concentrations (mg/L) at given pore volumes of all samples collected from a wetland cell loaded at a constant 3.8 L/m flow rate near the front, halfway through, and end of a SFCW.

	Front (Left)			Front (Right)		
Pore Vol.	**4 mm**	**10 cm**	**17 cm**	**4 mm**	**10 cm**	**17 cm**
0.00	0.0	0.0	0.0	0.0	0.0	0.0
0.02	17.8	10.2	6.9	31.1	25.1	15.6
0.07	23.0	37.0	45.9	22.1	35.4	40.3
0.14	6.9	9.3	15.6	3.8	8.2	10.6
0.21	3.0	4.5	7.9	3.2	4.7	8.6
0.27	1.8	2.5	5.1	2.0	2.4	5.1
0.34	1.7	2.3	2.5	1.9	2.2	2.2
0.41	1.6	2.0	2.3	1.6	2.0	2.4
0.48	1.3	1.5	1.9	1.3	1.5	2.2
0.55	1.1	1.3	1.7	1.1	1.2	1.6
0.62	1.0	1.2	1.2	1.0	1.1	1.3
0.69	0.9	1.1	1.0	0.8	1.0	1.2
0.75	0.7	0.8	0.9	0.7	0.8	0.9
0.82	0.6	0.7	0.7	0.6	0.7	0.8
0.89	0.6	0.7	0.7	0.6	0.7	0.9
0.96	0.6	0.7	0.7	0.6	0.6	0.7
1.03	0.6	0.6	0.6	0.5	0.6	0.7
1.10	0.5	0.6	0.6	0.5	0.6	0.7
1.17	0.5	0.6	0.6	0.5	0.6	0.7
	Halfway (Left)			**Halfway (Right)**		
Pore Vol.	**4 mm**	**10 cm**	**17 cm**	**4 mm**	**10 cm**	**17 cm**
0.00	0.0	0.0	0.0	0.0	0.0	0.0
0.08	76.4	73.2	70.1	79.7	70.1	43.8
0.15	16.3	19.4	15.7	17.8	15.0	25.1
0.22	5.6	5.6	6.4	5.8	4.7	9.0
0.29	2.6	1.9	2.6	2.5	2.4	4.0
0.35	1.8	1.3	1.7	1.6	1.6	1.8
0.42	1.3	1.0	1.2	1.1	1.1	1.3
0.49	2.4	2.2	2.8	2.5	2.4	3.2
0.56	2.3	0.8	2.2	2.1	1.8	2.0
0.63	0.7	1.9	0.8	0.8	0.7	2.1
0.70	1.7	1.6	2.2	1.6	1.6	2.2
0.77	1.4	1.6	1.6	1.6	1.6	1.6
0.83	1.3	2.2	1.4	1.3	1.2	1.4
0.90	1.2	1.0	1.2	1.0	1.0	1.3
0.97	0.9	2.4	0.6	0.9	2.3	2.4
1..4	0.6	0.6	0.6	0.6	2.4	0.6
1.11	0.5	0.5	0.6	0.5	0.5	0.6
1.18	0.5	0.5	0.5	0.8	0.8	0.5
1.25	0.7	0.8	0.8	0.7	0.8	0.8
1.31	0.7	0.7	0.8	0.7	0.7	0.8

Table B-1. (continued).

	End (Left)			End (Right)		
Pore Vol.	**4 mm**	**10 cm**	**17 cm**	**4 mm**	**10 cm**	**17 cm**
0.00	0.0	0.0	0.0	0.0	0.0	0.0
0.16	4.1	2.9	2.4	18.6	13.2	2.7
0.23	11.1	6.1	3.6	20.2	14.3	3.6
0.30	16.3	11.1	6.6	17.0	12.1	5.6
0.37	17.0	16.3	10.6	13.2	11.6	8.9
0.43	17.0	15.0	10.6	7.2	10.2	8.2
0.50	11.1	17.0	15.6	5.1	8.2	12.6
0.57	13.2	14.3	13.7	9.3	9.3	11.6
0.64	10.2	10.6	11.6	7.9	8.2	8.6
0.71	7.2	8.9	6.9	5.8	6.3	6.9
0.78	5.3	6.3	6.1	5.1	5.6	5.6
0.85	4.7	5.6	6.1	4.7	5.1	5.1
0.91	3.6	3.8	4.7	3.3	3.9	4.9
0.98	2.9	3.2	3.9	2.8	3.3	4.3
1.05	2.7	2.5	2.9	2.5	3.2	3.2
1.12	2.0	2.2	2.7	2.0	2.4	3.0
1.19	1.7	2.0	2.3	1.8	2.3	2.6
1.26	1.4	1.7	1.7	1.6	1.8	2.3
1.33	1.2	1.5	2.0	1.3	1.7	1.7

Table B-2. Br^- concentrations (mg/L) at given pore volumes of all samples collected from a wetland cell loaded at a constant 7.6 L/m flow rate near the front, halfway through and near the end of a SFCW.

	Front (Left)			Front (Right)		
Pore Vol.	**4 mm**	**10 cm**	**17 cm**	**4 mm**	**10 cm**	**17 cm**
0.00	0.0	0.0	0.0	0.0	0.0	0.0
0.02	0.7	0.8	0.8	0.7	0.7	1.1
0.06	113.8	76.7	73.5	87.5	70.3	67.3
0.13	10.3	12.8	32.0	8.6	9.8	34.9
0.19	3.4	5.1	7.9	3.0	3.4	8.2
0.26	2.0	2.4	3.3	1.8	2.2	4.7
0.32	1.4	1.6	2.0	1.3	1.6	2.6
0.39	1.1	1.2	1.4	1.0	1.1	1.7
0.45	1.2	1.0	1.2	0.8	1.0	1.4
0.51	0.8	0.8	0.9	0.7	0.8	1.2
0.58	0.7	0.8	0.8	0.7	0.8	1.2
	Halfway (Left)			**Halfway (Right)**		
Pore Vol.	**4 mm**	**10 cm**	**17 cm**	**4 mm**	**10 cm**	**17 cm**
0.00	0.0	0.0	0.0	0.0	0.0	0.0
0.03	1.3	1.3	1.3	1.3	1.2	1.4
0.10	6.1	2.6	2.9	12.8	7.9	4.1
0.16	54.2	54.2	51.9	49.7	54.2	54.2
0.22	16.6	17.4	15.9	11.7	11.2	13.4
0.29	6.4	6.9	6.1	4.5	4.9	5.8
0.35	3.4	3.6	3.3	2.4	2.4	2.5
0.42	2.1	2.2	1.9	1.6	1.6	1.6
0.48	1.4	1.4	1.4	1.1	1.1	1.1
0.55	1.1	1.1	1.2	0.8	0.8	0.8
0.61	1.1	1.1	1.0	0.8	0.9	1.0
	End (Left)			**End (Right)**		
Pore Vol.	**4 mm**	**10 cm**	**17 cm**	**4 mm**	**10 cm**	**17 cm**
0.00	0.0	0.0	0.0	0.0	0.0	0.0
0.06	1.8	2.1	2.6	1.8	2.0	2.0
0.13	6.8	2.1	2.4	8.1	3.7	2.1
0.19	4.4	2.2	2.3	31.4	17.0	4.2
0.26	4.6	3.1	2.4	24.2	17.0	5.2
0.32	7.7	4.6	3.2	15.6	13.7	7.1
0.39	10.5	8.1	6.0	10.1	11.5	9.2
0.45	12.0	9.6	6.8	7.4	9.2	9.6
0.51	11.5	10.1	8.1	5.0	7.4	9.2
0.58	9.6	8.8	7.7	4.2	6.2	8.1
0.64	8.5	7.4	6.5	3.1	4.6	6.8
0.71	6.0	6.2	5.7	2.4	3.7	5.5
0.77	5.0	5.2	4.8	1.8	3.2	4.6
0.84	7.2	7.9	8.3	3.6	5.3	6.4
0.90	6.4	6.9	6.6	3.4	4.9	6.1
0.96	3.4	5.1	5.8	2.3	3.3	4.5
1.03	4.1	4.7	4.5	2.5	3.3	4.1
1.09	3.4	2.8	4.9	1.9	3.8	3.2
1.16	3.6	2.6	3.2	1.6	1.9	2.2
1.22	1.8	2.2	2.1	1.1	1.3	0.8
1.29	1.3	1.6	1.9	0.8	1.0	1.4

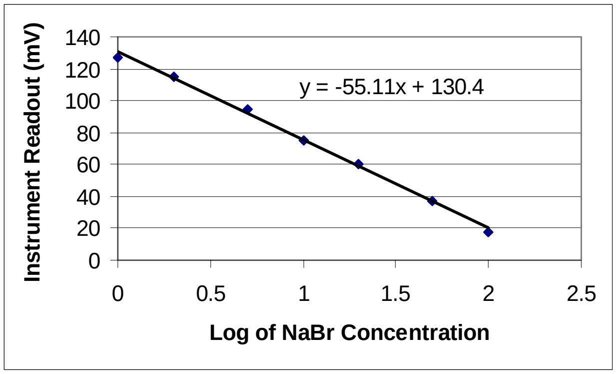


Figure B-1. Calibration curve for the samples collected from the front row of sampling ports during the flow study conducted at a 3.8 L/m constant flow rate.

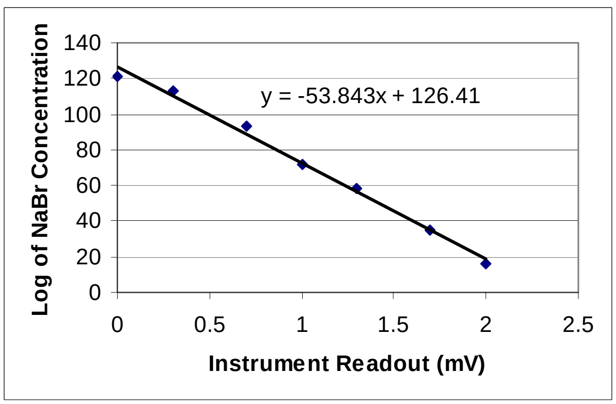


Figure B-2. Calibration curve for the samples collected from the middle row of sampling ports during the flow study conducted at a 3.8 L/m constant flow rate.

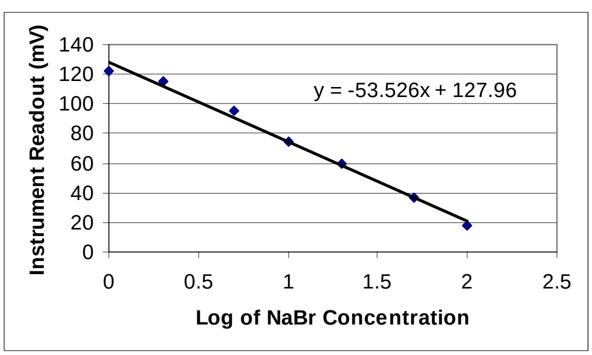


Figure B-3. Calibration curve for the samples collected from the end row of sampling ports during the flow study conducted at a 3.8 L/m constant flow rate.

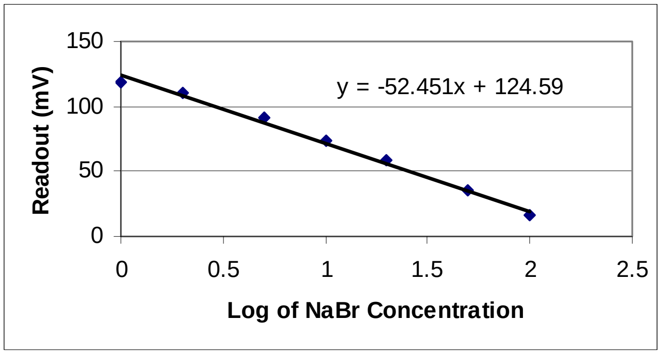


Figure B-4. Calibration curve for the samples collected from the front row of sampling ports during the flow study conducted at a 7.6 L/m constant flow rate.

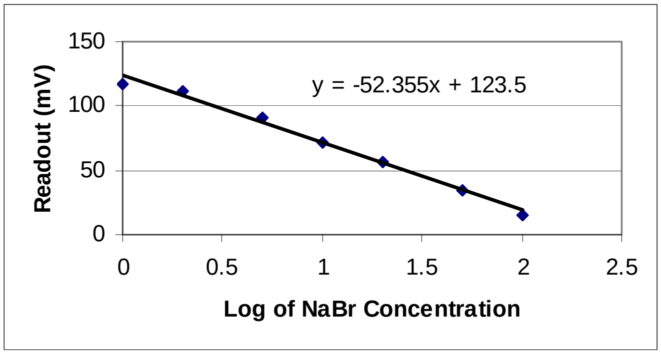


Figure B-5. Calibration curve for the samples collected from the middle row of sampling ports during the flow study conducted at a 7.6 L/m constant flow rate.

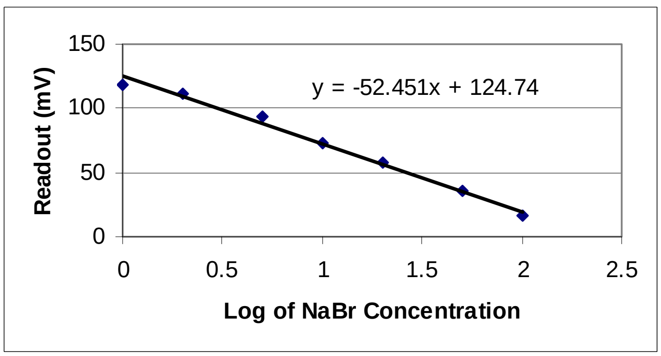


Figure B-6. Calibration curve for the samples collected from the end row of sampling ports during the flow study conducted at a 7.6 L/m constant flow rate.

APPENDIX C

Table C-1. Concentrations (mg/L) of NaBr at given pore volumes of all samples collected at Site 1 at the front, 2.5 m from the header, 4.5 m from the header and at the end of the wetland loaded through a leaching chamber.

Pore Vol.	Front of the wetland (0.5 m from header) A*	B	C	D	2nd row (2.5 m from header) E	F	G	H	3rd row (4.5 m from header) I	J	K	L	End of the wetland M	N	O	P
0.01	2.4	1.3	0.9	1.9	4.0	1.8	4.5	3.7								
0.05	6.5	6.0	10.3	3.3	3.6	2.1	2.7	4.2	2.4	2.3	2.5	1.4				
0.11	3.6	8.2	5.5	12.6	3.4	6.7	8.7	4.3	2.4	2.4	2.9	1.4	0.7	1.1	1.4	0.6
0.16	6.5	5.3	3.0	15.3	3.8	6.2	15.1	10.2	2.6	2.6	4.1	1.7	0.7	1.2	1.3	0.6
0.22	9.2	3.2	1.8	10.7	4.2	15.1	11.1	17.7	2.8	3.0	5.4	1.6	0.7	1.2	1.4	0.6
0.27	7.0	2.2	1.2	7.6	6.9	16.4	8.7	17.7	3.1	3.3	8.0	2.3	0.7	1.3	1.5	0.7
0.33	6.0	1.4	0.8	6.0	12.0	13.5	5.9	14.6	4.3	5.6	9.0	3.5	0.8	1.7	1.7	0.7
0.38	4.4	0.9	0.6	4.5	16.4	9.5	5.9	10.6	6.1	9.0	7.7	4.8	0.8	1.5	1.9	0.7
0.43	2.8	0.8	0.5	3.2	15.7	6.9	2.2	6.9	8.0	9.4	6.9	5.2	0.9	1.7	2.5	0.8
0.49	1.9	0.7	0.4	2.2	9.1	5.9	2.7	4.7	10.1	8.3	4.1	5.0	0.9	2.1	3.3	0.8
0.54	1.5	0.5	0.4	1.5	6.7	3.8	2.4	3.2	10.1	6.9	3.3	4.8	0.9	3.0	5.1	0.7
0.60									8.7	4.8	2.5	4.1	1.0	3.8	6.0	0.9
0.65									7.1	4.0	2.1	3.3	1.0	4.9	5.7	0.9
0.71													1.1	5.7	4.9	1.0
0.76													1.9	6.2	4.5	1.5
0.81													1.7	5.5	3.5	1.9

* Letters correspond to sampling ports shown in the diagram

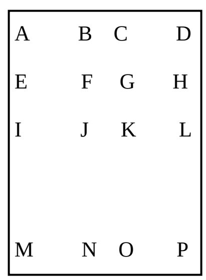


Table C-2. Concentrations (mg/L) of NaBr at given pore volumes of all samples collected at Site 2 at the front, 2.5 m from the header, 4.5 m from the header and at the end of the wetland loaded through a leaching chamber.

Pore Vol.	Front of the wetland (0.5 m from header)				2nd row (2.5 m from header)				3rd row (4.5 m from header)				End of the wetland			
	A*	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
0.01	2.2	1.6	15.6	4.8	0.5	2.3	3.0	2.5								
0.06	3.4	12.0	5.7	48.8	0.9	8.5	3.5	5.7	0.3	1.8	1.9	2.1				
0.13	16.3	4.8	3.2	44.7	1.2	11.0	3.7	27.7	0.4	13.8	2.9	14.4	0.6	1.3	1.3	1.1
0.19	44.7	2.3	2.0	20.3	3.9	10.6	3.2	26.5	0.5	15.0	3.9	27.7	0.6	1.7	1.7	2.2
0.26	35.9	1.1	1.1	6.8	9.3	6.3	2.2	13.2	1.2	11.1	3.0	19.5	0.8	6.4	3.3	17.5
0.32	20.3	0.8	0.7	3.5	14.4	4.0	1.5	6.8	2.2	6.8	1.7	11.6	2.6	6.1	3.5	21.8
0.38	12.6	0.8	0.8	2.1	15.7	2.4	1.0	3.7	4.2	4.4	1.4	6.5	5.4	5.4	3.2	15.3
0.45	7.1	0.5	0.6	1.3	13.7	1.7	0.8	2.5	6.3	2.7	1.1	2.5	7.6	3.8	2.1	9.5
0.51	2.5	0.5	0.7	0.9	11.5	1.1	0.6	1.4	6.5	1.7	0.9	1.8	8.7	2.9	1.7	6.1
0.58	1.5	0.4	0.4	0.5	7.8	0.7	0.5	0.8	6.3	1.2	0.6	1.4	8.7	2.1	1.2	3.2
0.64	0.9	0.3	0.4	0.5	5.5	0.6	0.5	1.2	5.5	1.1	0.5	1.4	7.6	1.9	1.0	2.1
0.71	0.7	0.4	0.3	0.5	4.4	0.5	0.4	0.9	4.8	1.0	0.5	1.2	7.0	1.1	0.8	no data
0.77	0.5	0.3	0.3	0.4	3.5	0.4	0.4	0.8	3.5	0.8	0.4	no data	5.1	1.0	0.9	1.3
0.83	0.4	0.2	0.2	0.3	3.2	0.3	0.3	0.8	2.5	0.9	0.4	no data	4.1	0.9	0.8	1.1
0.90	0.3	0.2	0.2	0.2	2.2	0.2	0.2	0.8	2.3	0.6	0.4	1.1	3.3	0.8	0.6	1.0
0.96					2.2	0.2	0.2	0.7	1.8	0.6	0.3	0.7	2.7	0.8	0.7	1.0
1.03					2.0	0.2	0.2	0.7	1.5	0.7	0.3	0.6	2.1	0.7	0.6	0.9
1.09									1.3	0.6	0.3	0.7	1.8	0.7	0.5	0.8

***** Letters correspond to sampling ports shown in the diagram

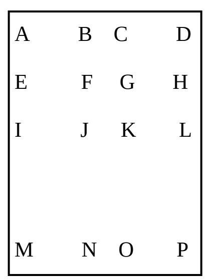


Table C-3. Concentrations (mg/L) of NaBr at given pore volumes of all samples collected at Site 3 at the front and end of the wetland loaded through a leaching chamber.

			Front of the wetland		
Pore Vol.	**A***	**B**	**C**	**D**	**E**
0.07	58.6	no data	55.6	no data	38.7
0.15	47.1	54.9	60.8	83.0	83.0
0.22	33.9	41.4	50.6	57.2	56.4
0.30	37.5	30.4	42.4	35.2	29.7
0.37	20.0	17.9	24.0	23.1	25.9
0.45	16.1	12.1	17.3	18.0	19.5
			End of Wetland		
Pore Vol.	**F**	**G**	**H**	**I**	**J**
0.30	5.7	no data	5.8	no data	5.8
0.37	5.7	no data	5.8	no data	5.8
0.45	6.1	no data	6.3	no data	6.8
0.52	6.7	8.6	6.6	7.7	7.9
0.60	8.5	7.5	7.2	7.2	11.9
0.67	13.9	7.7	9.5	8.3	18.2
0.75	15.5	8.6	13.2	10.8	19.2
0.82	27.8	12.9	20.7	16.7	24.7
0.90	22.4	23.1	34.0	26.7	20.5

* Letters correspond to sampling ports shown in the diagram

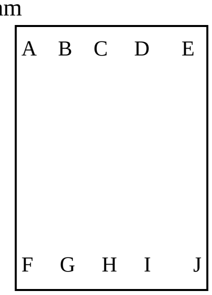
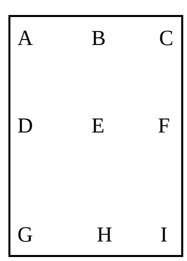


Table C-4. Concentrations (mg/L) of NaBr at given pore volumes of all samples collected at Site 4 at the front, midway through and end of the wetland loaded through a leaching chamber.

	Front		
Pore Vol.	**A***	**B**	**C**
0.07	45.9	17.6	8.5
0.15	56.8	20.6	32.5
0.22	38.2	21.5	43.3
0.30	25.6	19.5	35.5
0.37	16.1	16.8	23.9
0.45	11.1	12.8	16.7
	Middle		
Pore Vol.	**D**	**E**	**F**
0.07	3.5	3.8	3.6
0.15	3.6	3.3	3.4
0.22	3.5	3.9	4.5
0.30	4.3	4.0	4.0
0.37	4.6	4.4	4.1
0.45	14.8	5.4	6.2
0.52	22.2	8.0	13.7
0.60	26.6	20.0	25.7
0.67	13.5	25.2	21.9
0.75	16.4	23.9	19.3
0.82	15.8	19.3	21.4
0.90	15.2	15.9	19.2
	End		
Pore Vol.	**G**	**H**	**I**
0.37	6.0	5.2	5.4
0.45	4.3	4.3	4.4
0.52	4.3	4.3	4.6
0.60	4.4	4.3	4.6
0.67	4.8	4.4	4.7
0.75	9.1	6.0	5.3
0.82	13.3	6.3	5.6
0.90	16.9	5.8	5.8
0.97	20.8	7.2	7.8
1.05	20.3	6.7	9.6
1.12	19.6	7.7	12.0

* Letters correspond to sampling ports shown in the diagram



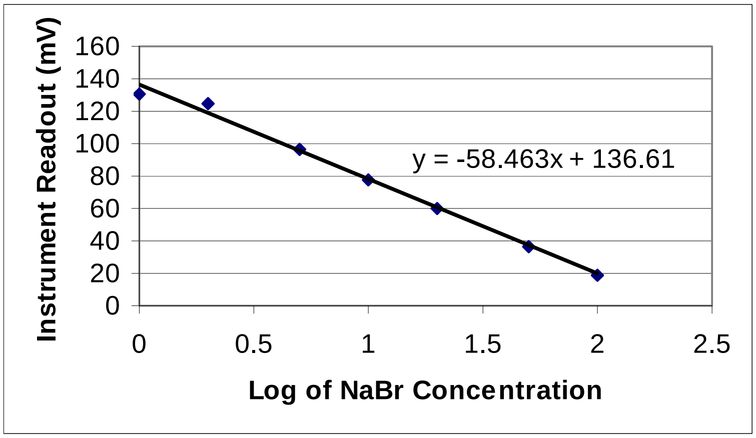


Figure C-1. Calibration curve used to derive NaBr concentrations from sampling ports 0.5 m from the header during tracer study at Site 1.

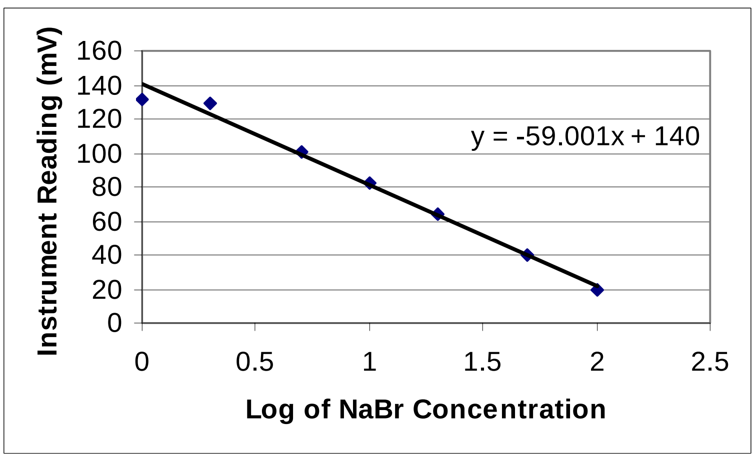


Figure C-2. Calibration curve used to derive NaBr concentrations from sampling ports 2.5 m from the header during tracer study at Site 1.

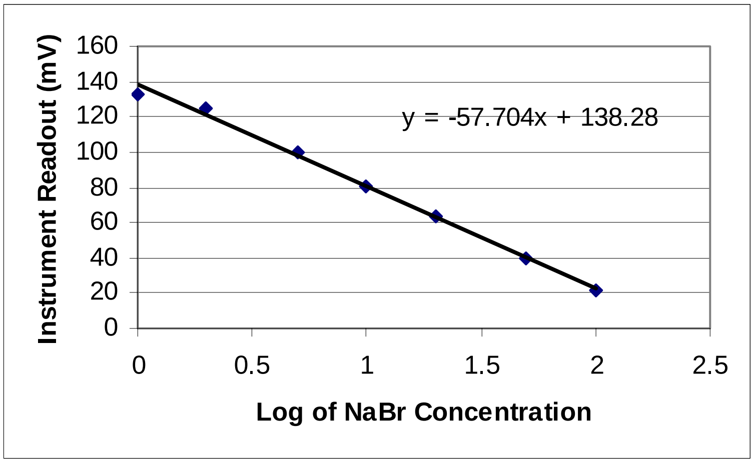


Figure C-3. Calibration curve used to derive NaBr concentrations from sampling ports 4.5 m from the header during tracer study at Site 1.

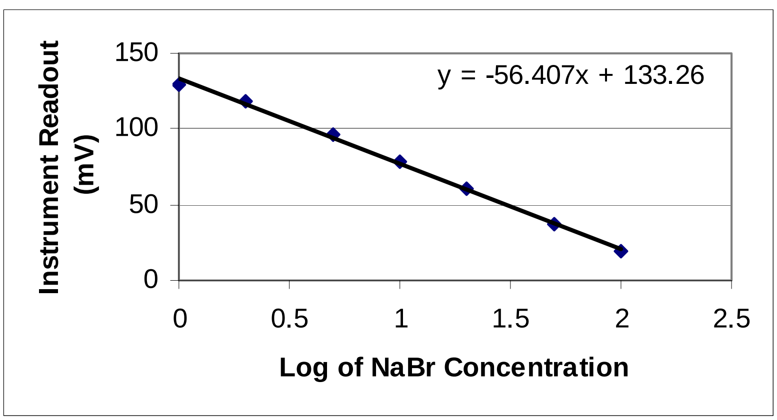


Figure C-4. Calibration curve used to derive NaBr concentrations from sampling ports 0.5 m from the end of the wetland during tracer study at Site 1.

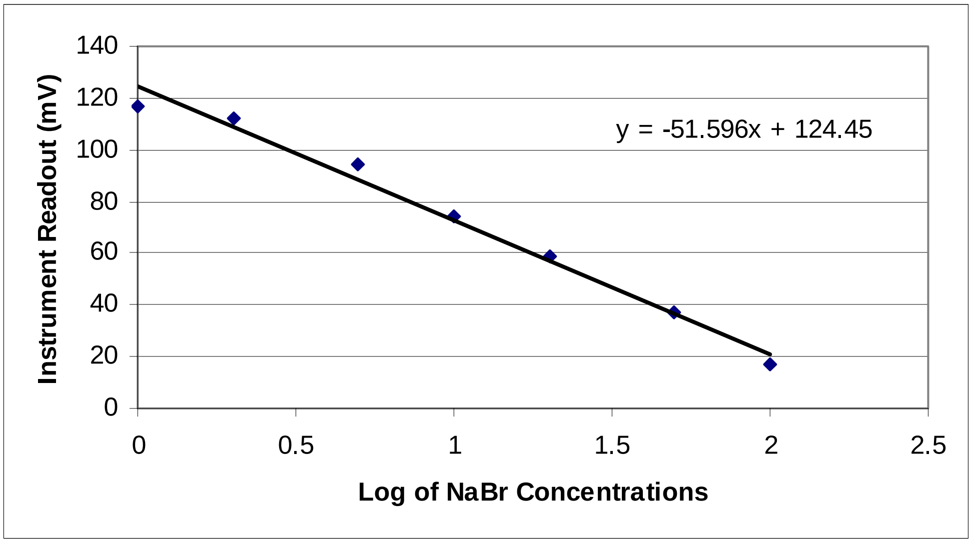


Figure C-5. Calibration curve used to derive NaBr concentrations from sampling ports 0.5 m from the header during tracer study at Site 2.

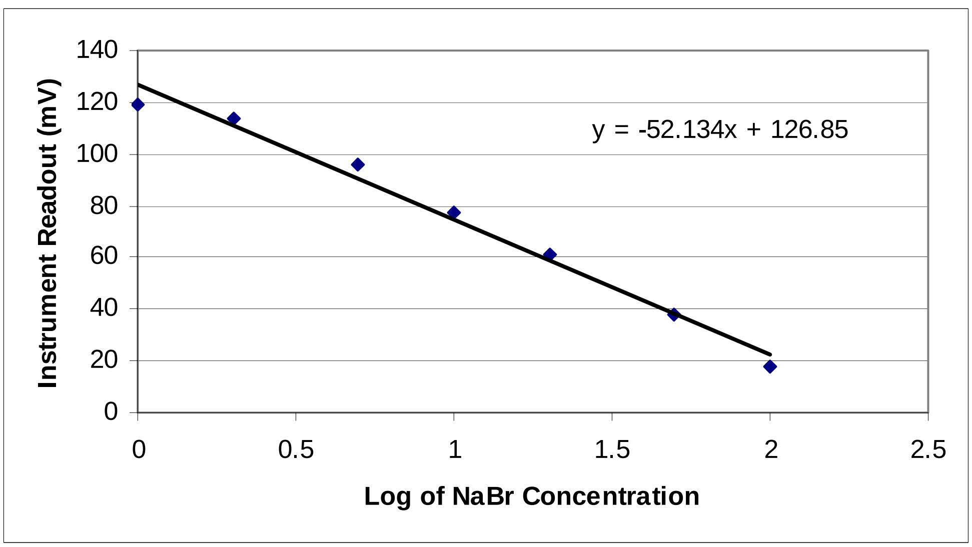


Figure C-6. Calibration curve used to derive NaBr concentrations from sampling ports 2.5 m from the header during tracer study at Site 2.

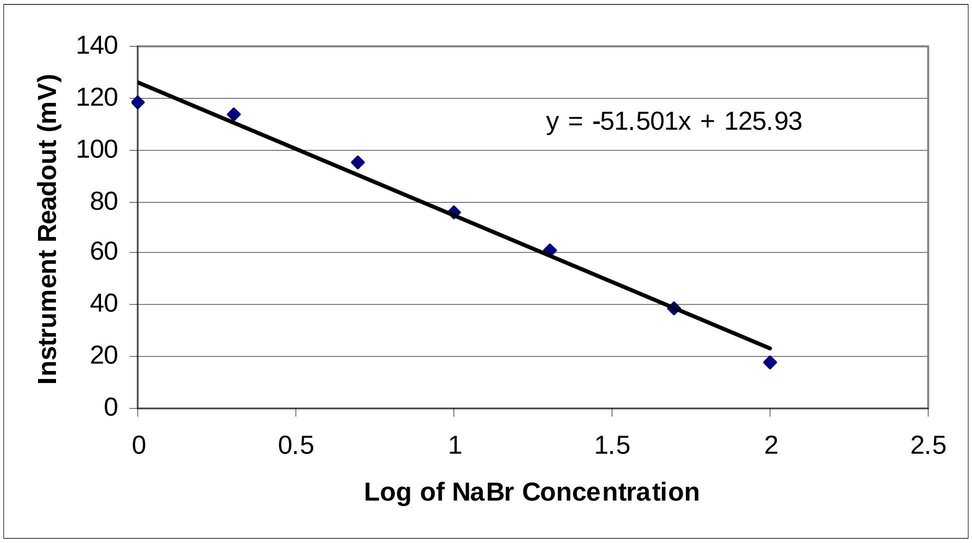


Figure C-7. Calibration curve used to derive NaBr concentrations from sampling ports 4.5 m from the header during tracer study at Site 2.

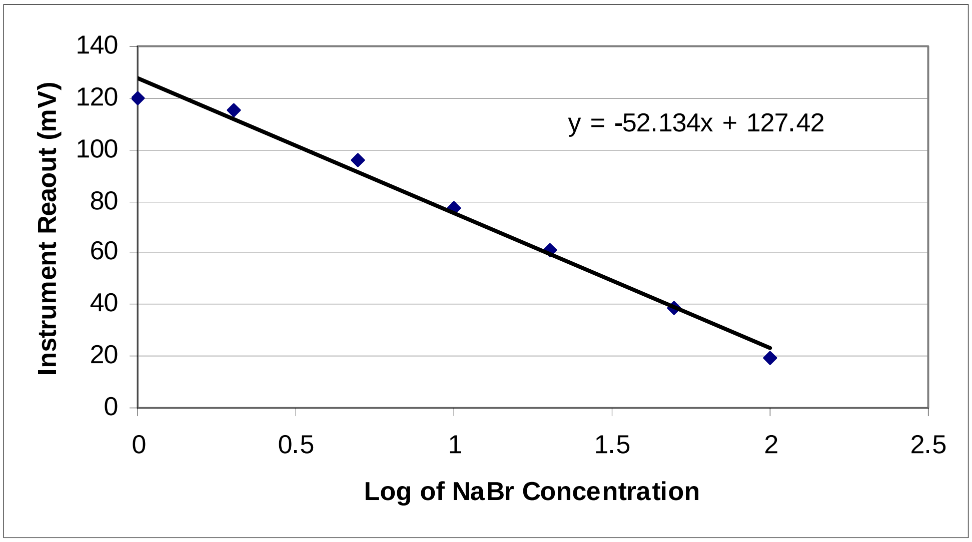


Figure C-8. Calibration curve used to derive NaBr concentrations from sampling ports 0.5 m from the end of the wetland during tracer study at Site 2.

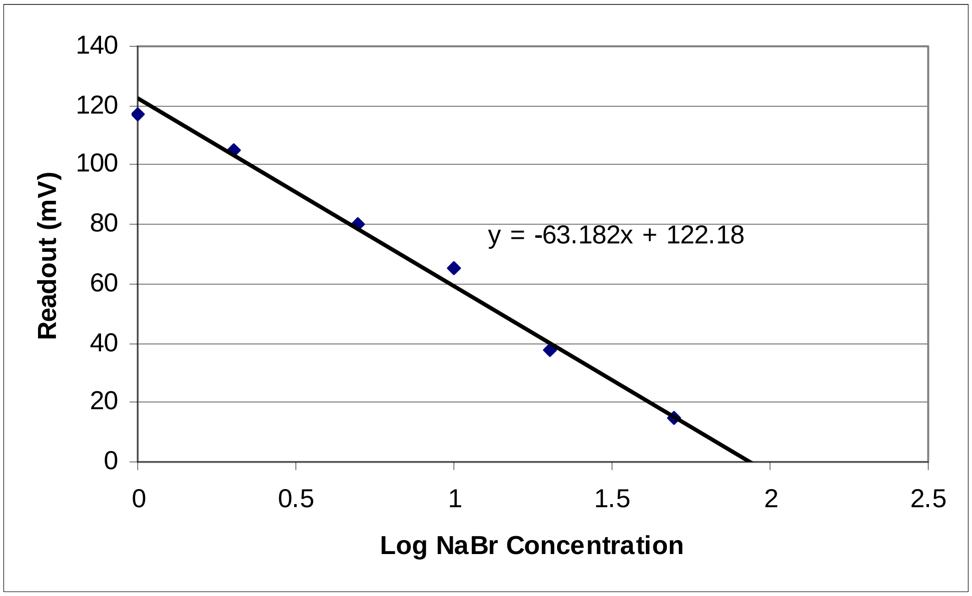


Figure C-9. Calibration curve used to derive NaBr concentrations from all samples collected during the tracer study at Site 3.

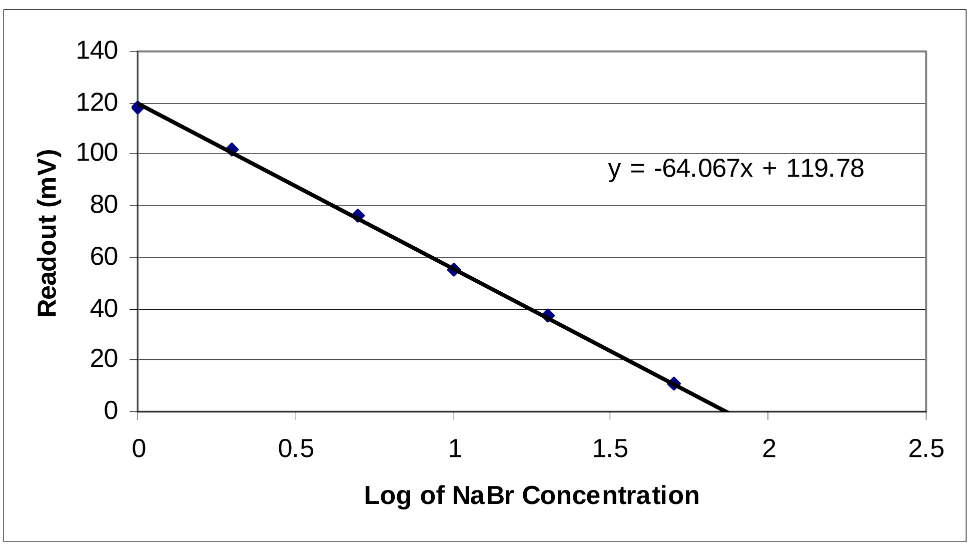


Figure C-10. Calibration curve used to derive NaBr concentrations from all samples collected during the tracer study at Site 4.

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